



Probing Quark Gluon Plasma with quarkonium production

C. Hadjidakis

► To cite this version:

C. Hadjidakis. Probing Quark Gluon Plasma with quarkonium production. The Workshop on Charmonium production and decays: new results and perspectives, Mar 2013, Orsay, France. in2p3-00856695

HAL Id: in2p3-00856695

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Submitted on 2 Sep 2013

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Probing Quark Gluon Plasma with quarkonium production

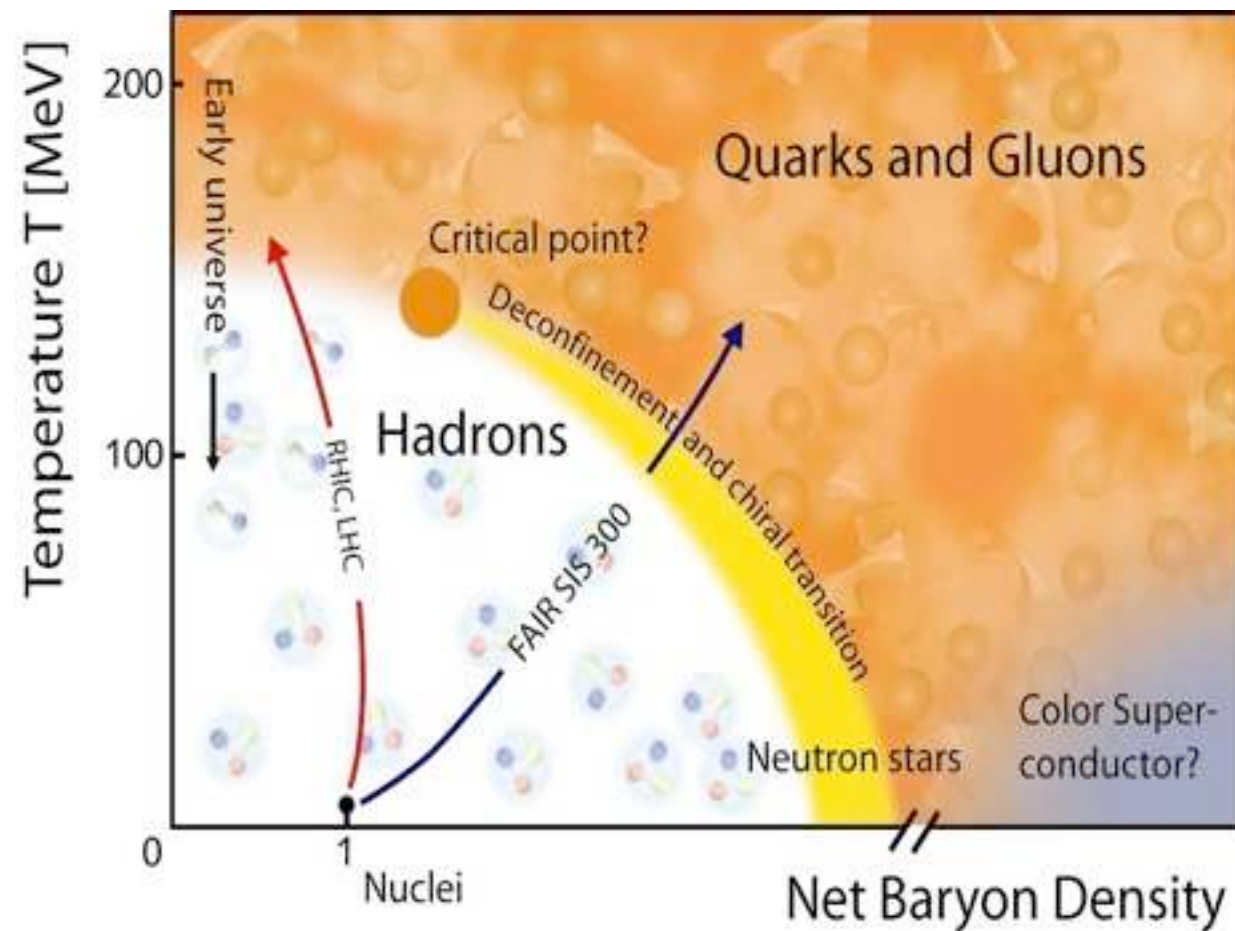
Cynthia Hadjidakis

Charmonium workshop

LAL-Orsay March 7th 2013

- Exploring the Quark Gluon Plasma
- A particular probe: the quarkonium family
- Selected results from SPS to LHC

The QCD phase diagram and the QGP



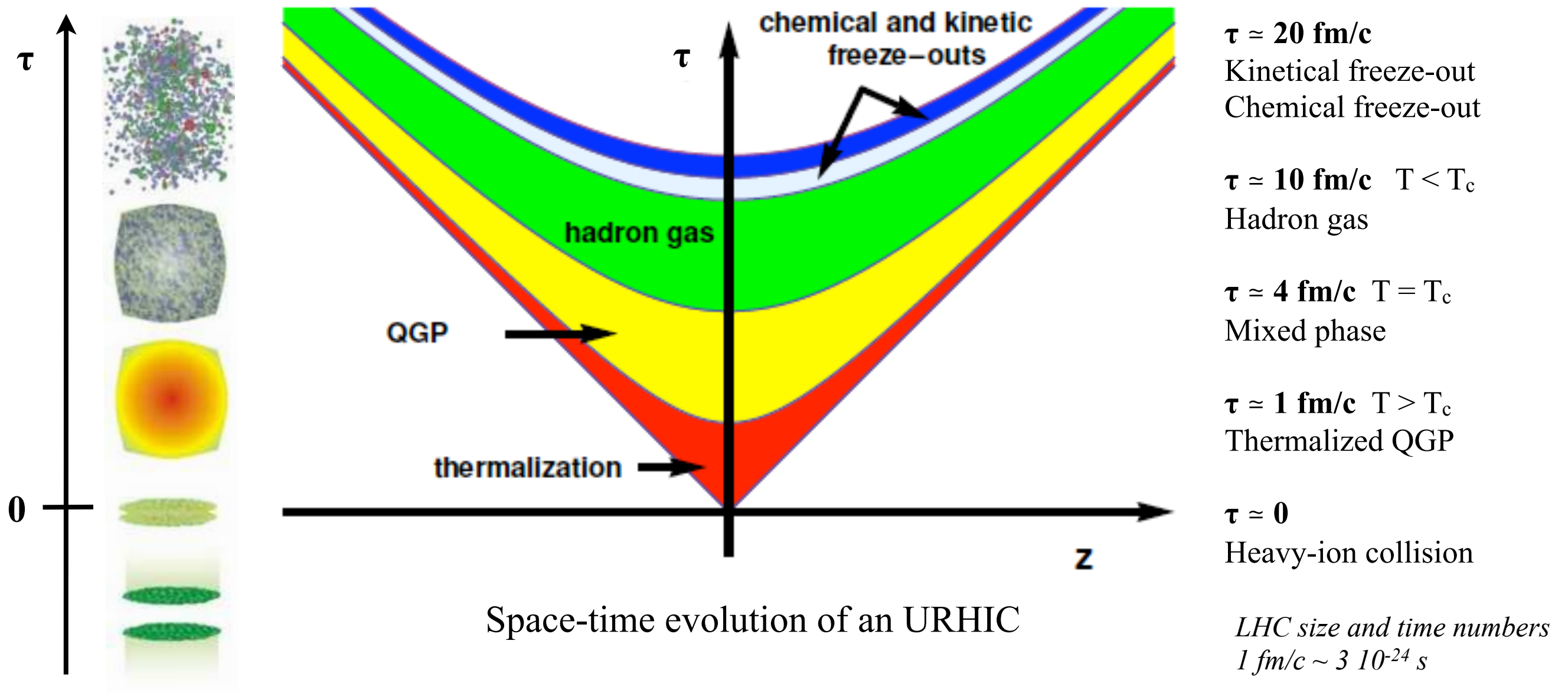
Nuclear matter at high temperature and high density = **Quark Gluon Plasma** (QGP)

- Partons are deconfined (not bound into composite object)
- Chiral symmetry is restored (partons are massless)

From lattice QCD: At $\mu_b = 0$, $T_c = 170$ MeV ($\epsilon_c = 1$ GeV/fm³)

Ultra-relativistic heavy ion collision experiments
Search for the QGP phase and characterize it

A little bang in ultra-relativistic heavy ion collisions (URHIC)

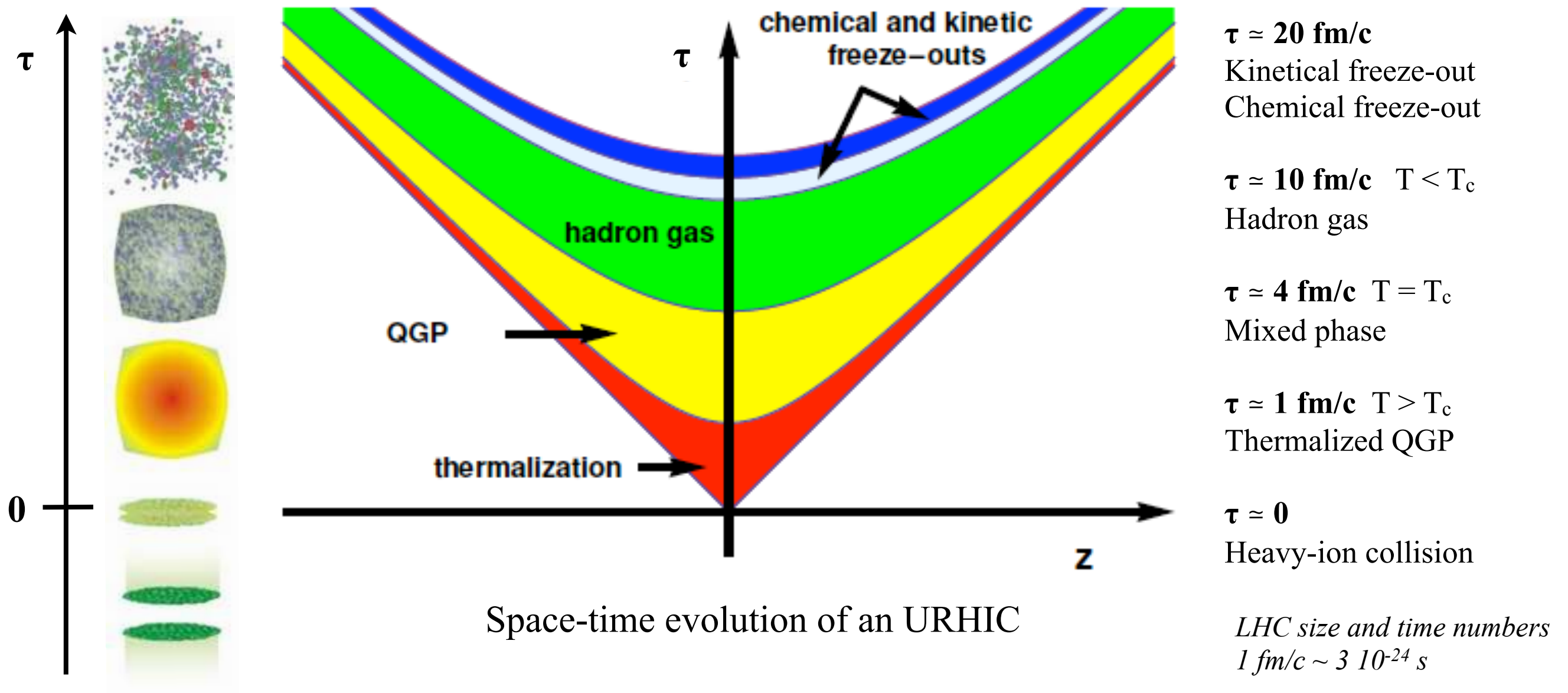


Space-time evolution of an URHIC

QGP volume $\approx 300 \text{ fm}^3$

LHC size and time numbers
 $1 \text{ fm/c} \sim 3 \cdot 10^{-24} \text{ s}$

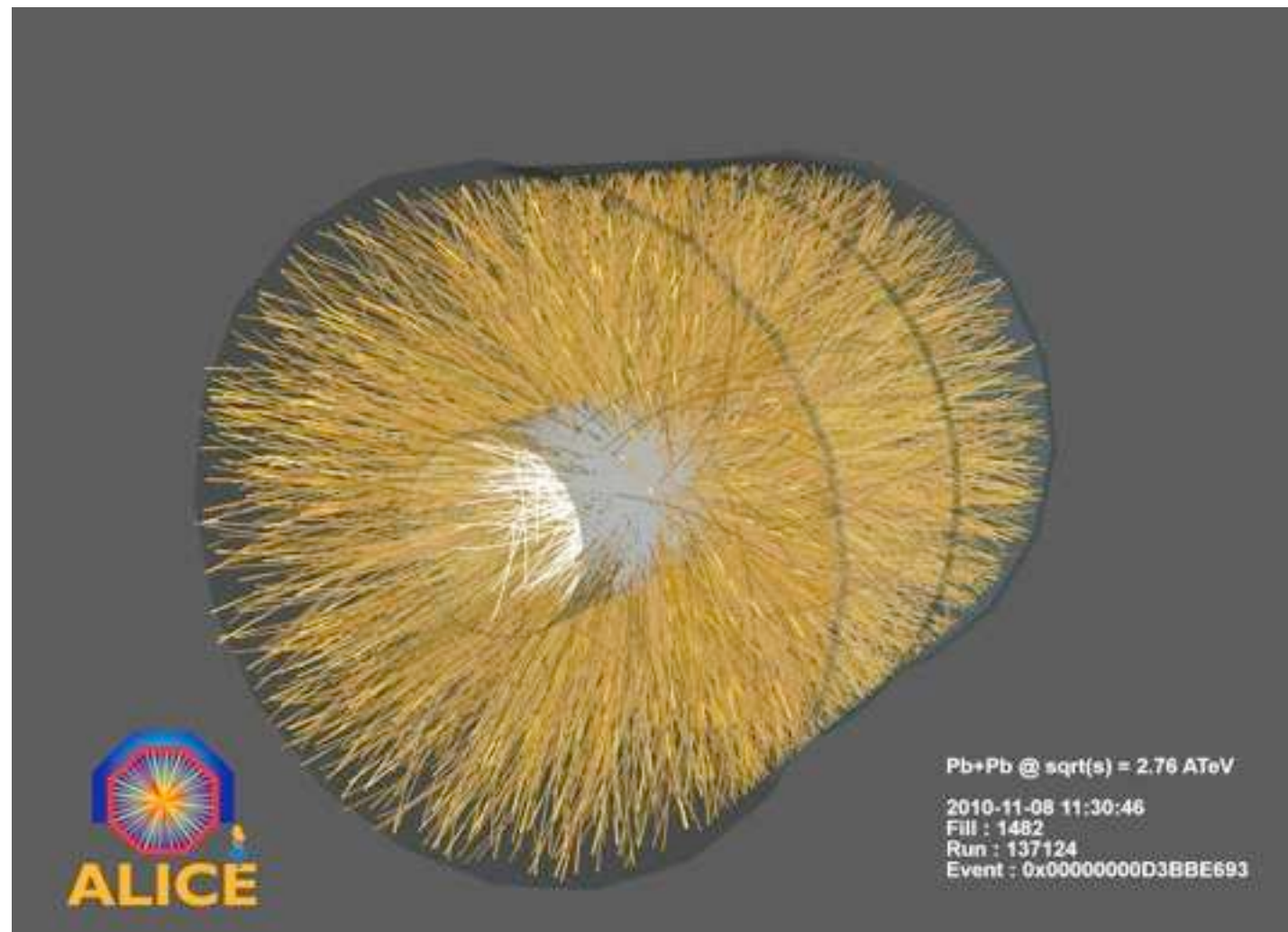
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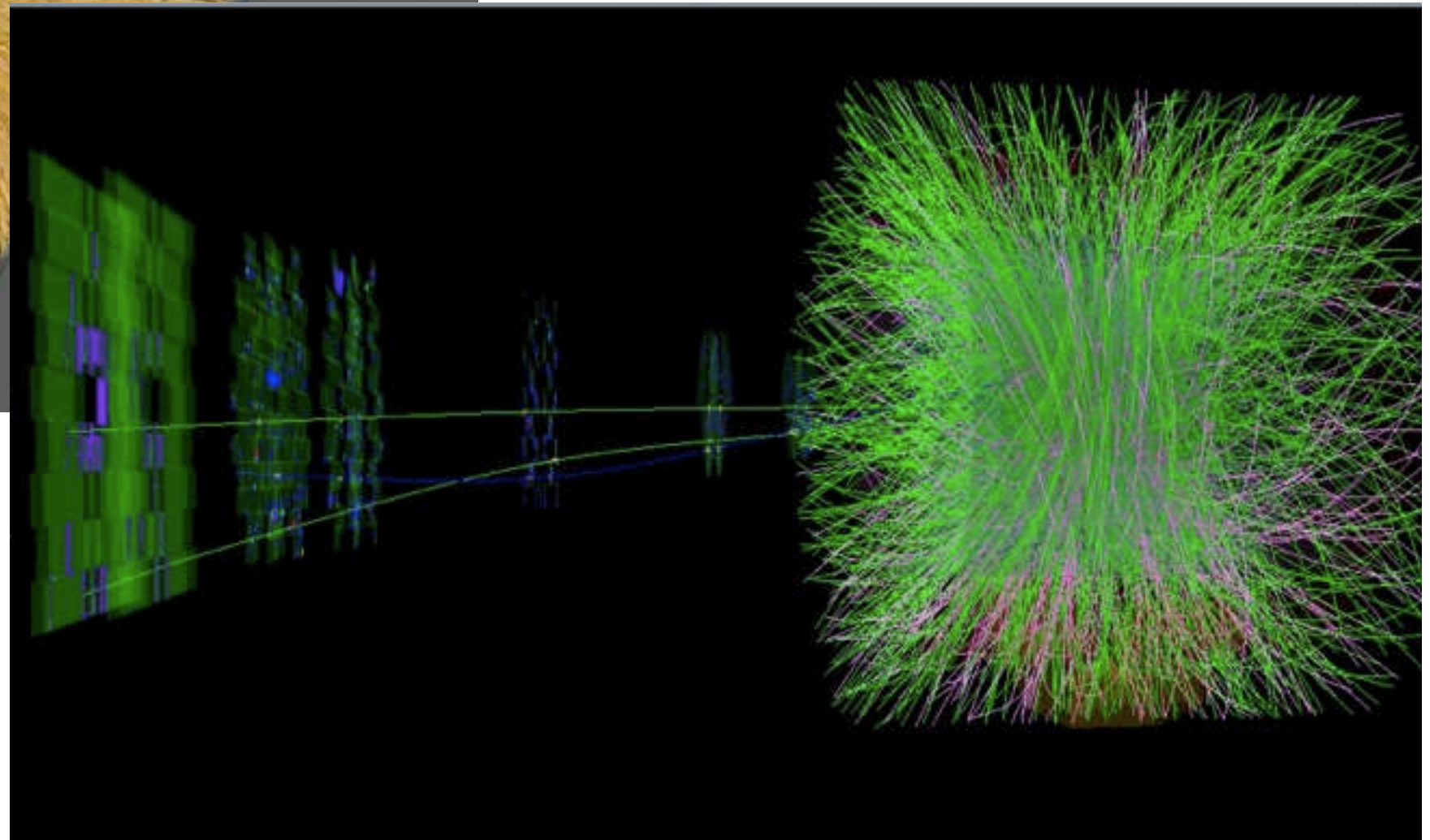
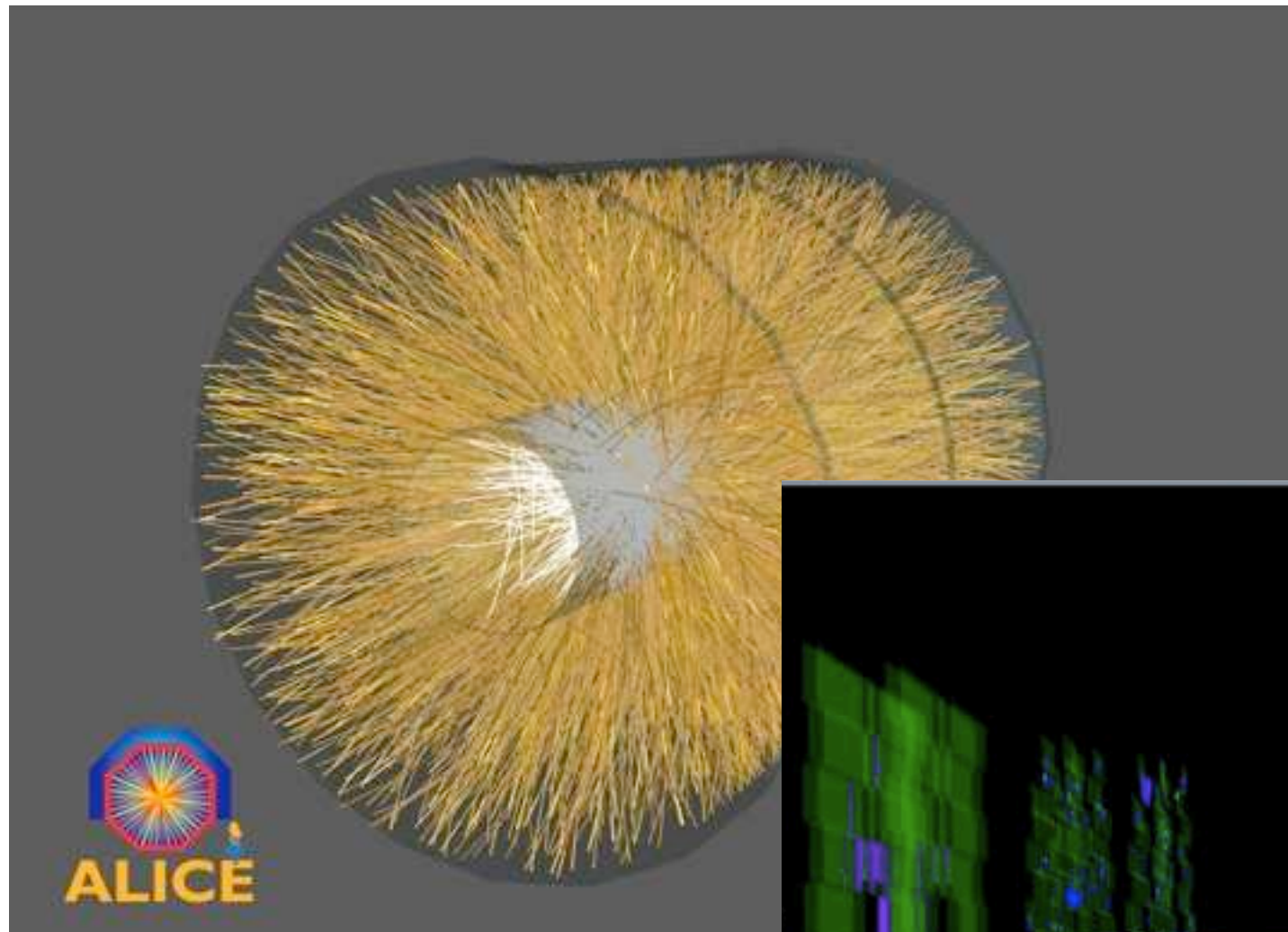
QGP volume $\approx 300 \text{ fm}^3$

At larger energy: larger, hotter, denser, longer life-time plasma

... and finally in the experiment - ALICE



... and finally in the experiment - ALICE



Probing the QGP

Many observables to probe the QGP

- Global observables: multiplicity, total transverse energy, ...
- Initial state observables: probes not affected by QGP as direct γ , $W^{+/-}$, Z^0
- Final state observables: hadron kinematic distributions, hadron species production, flow, high p_T correlations, ...
- Hard probes (first stage of the collisions): high p_T particles, jets, open and hidden heavy flavour particles, ...

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2000 - SPS @ CERN - Evidence of a new state of matter

2005 - RHIC @ BNL - QGP is a very strongly interacting (almost) perfect liquid

01/2010 - RHIC @ BNL - Highest man-made temperature (4 trillion $^{\circ}\text{C}$) in the Guinness Record

12/2010 - ALICE @ LHC - QGP formed at LHC has a temperature 30% higher than RHIC

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Heavy-ion experiments: from discovery to **quantitative characterization**: measuring QGP parameters (energy, density, size, lifetime, temperature,...)

Probing the QGP with quarkonia

Properties of quarkonium states

- made of heavy quark and anti-quark: $m_c = 1.2\text{-}1.4\text{ GeV}$ and $m_b = 4.6\text{-}4.9\text{ GeV}$
- produced in the initial hard partonic collisions ($\tau \approx 1/m_Q \approx 0.05\text{-}0.15\text{ fm/c}$)
- stable and tightly bound: $M_{c\bar{c}} < 2 M_D$ and $M_{b\bar{b}} < 2 M_B$

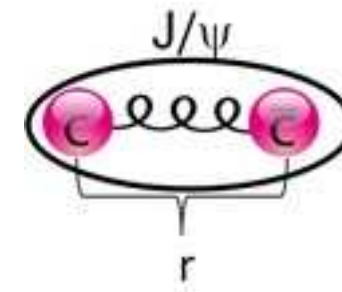
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At $T = 0$, in the vacuum, Cornell potential

- 2 terms:
- $$V(r) = -\frac{\alpha}{r} + kr$$
- Coulombian contribution (gluon exchange)
 - Confinement contribution



Probing the QGP with quarkonia

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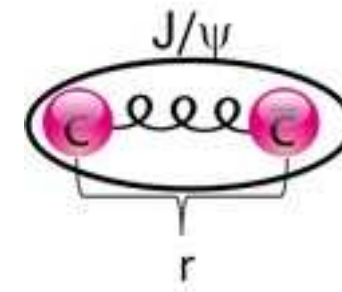
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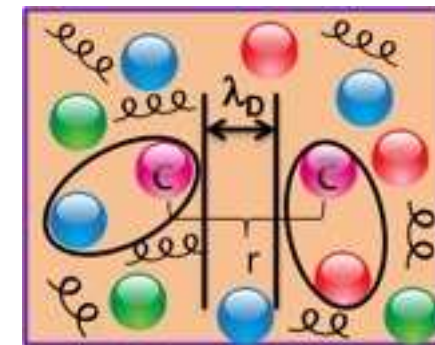
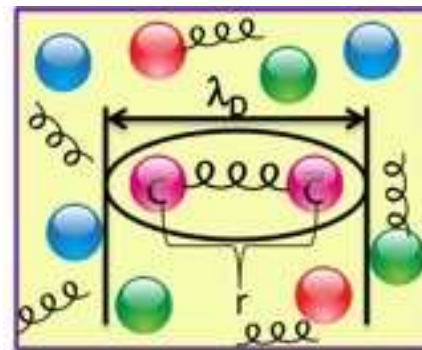


At $T \gg 0$, debye screening induced by the high density of colour charges

Matsui, Satz PLB178(1986),416

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

λ_D : Debye screening radius
 λ_D decreases with T



Temperature

→ Melting of quarkonia at high temperature for $\lambda_D < \text{Quarkonium state radius}$

Probing the QGP with the quarkonium family

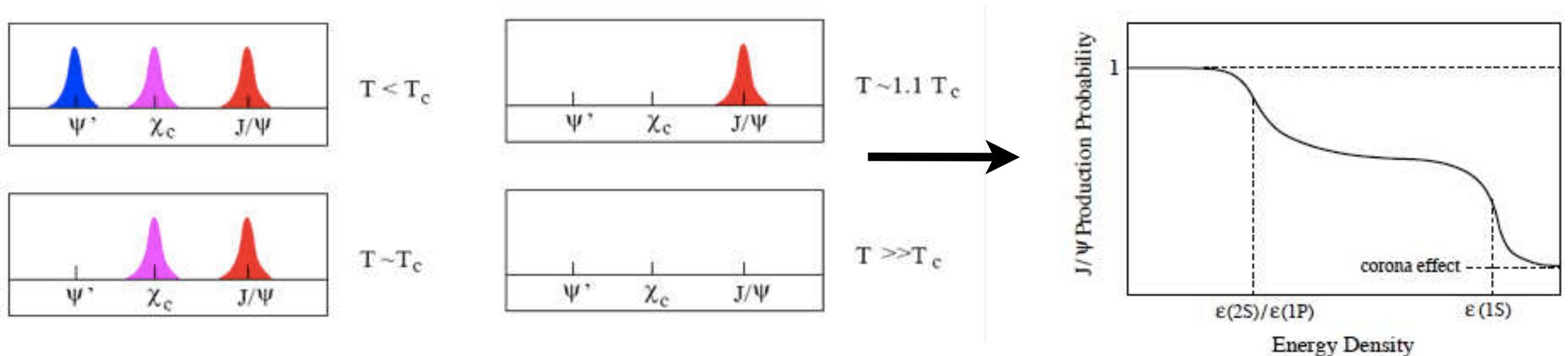
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Probing the QGP with the quarkonium family

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Example of measured J/Ψ

prompt $J/\Psi \approx 60\%$ direct $J/\Psi + 30\% \chi_c + 10\% \Psi(2S)$

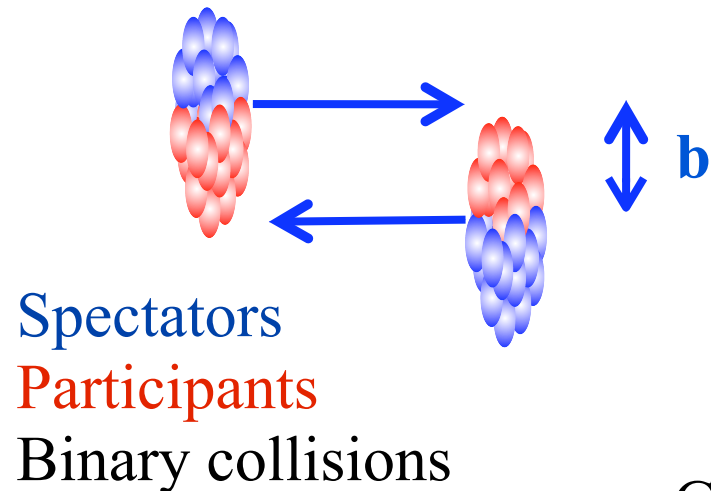


Sequential suppression of the quarkonium family: **QGP thermometer**

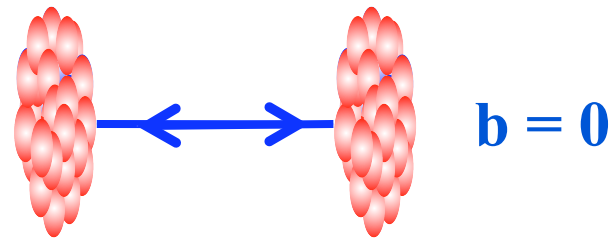
Centrality of the collisions

Centrality of the collisions

semi-central coll.



central coll.



	$N_{\text{part}} = 2$	$N_{\text{coll}} = 1$
	$N_{\text{part}} = 5$	$N_{\text{coll}} = 6$
Pb-Pb cent.	$N_{\text{part}} = 380$	$N_{\text{coll}} = 1700$

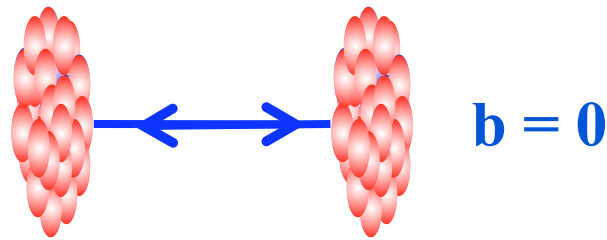
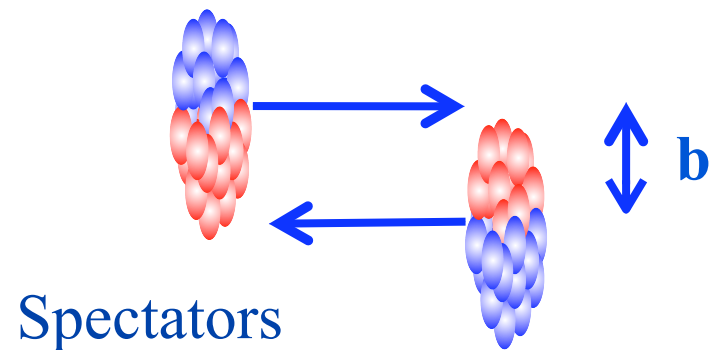
→ Glauber model used to determine the geometry of the collision

Centrality of the collisions

Centrality of the collisions

semi-central coll.

central coll.



Spectators
Participants

Binary collisions

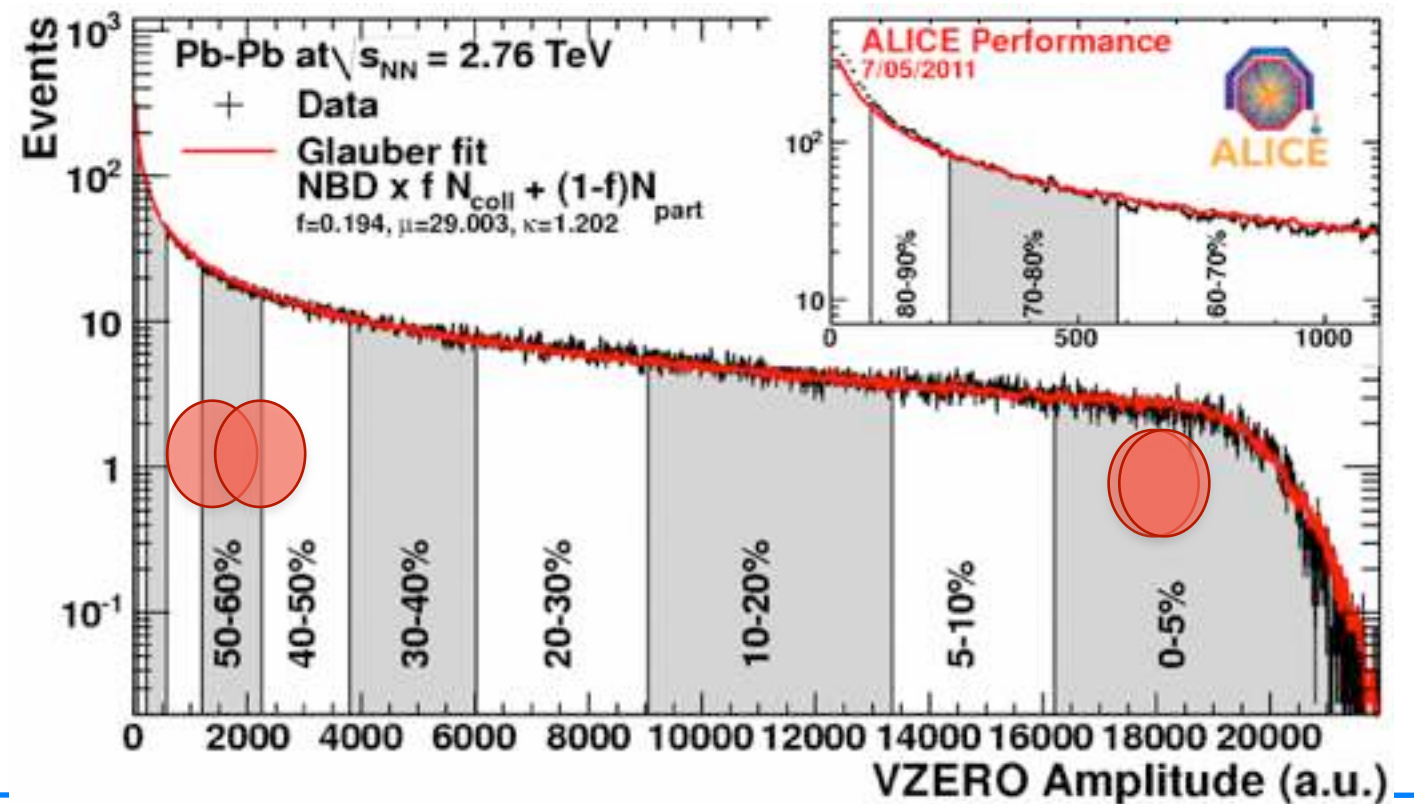
	$N_{\text{part}} = 2$	$N_{\text{coll}} = 1$
	$N_{\text{part}} = 5$	$N_{\text{coll}} = 6$
Pb-Pb cent.	$N_{\text{part}} = 380$	$N_{\text{coll}} = 1700$

→ Glauber model used to determine the geometry of the collision

Centrality determination

Multiplicity measurements with forward or central detectors

Relate the measured multiplicity in A-A collisions to N_{part} and N_{coll}



Nuclear modification factor

Nuclear modification factor

$$R_{AA} = \frac{dN^{AA}/dp_T dy}{\langle N_{coll} \rangle dN^{pp}/dp_T dy}$$

Hard process: scale with N_{coll}

- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression

References

- Production in p-p at the same energy (whenever possible): reference for R_{AA}
- Production in p-A at the same energy (whenever possible): cold nuclear matter determination

Cold nuclear matter (CNM)

- Initial state effect: nuclear shadowing (npdf) -or gluon saturation in the nucleus-, parton energy loss, multiple elastic scatterings of partons (Cronin effect), ...
- Final state effect: breakup of precursor quarkonia by nucleon collisions in the crossing nuclear matter (nuclear absorption), energy loss, ...

Results from SPS and RHIC

PHENIX Coll. PRL98 (2007) 232301
SPS Coll. @ QM06

SPS: NA38, NA50, NA60

$\sqrt{s_{NN}} = 17$ GeV

In-In / Pb-Pb

$\sqrt{s_{NN}} = 19$ GeV

S-U

RHIC: PHENIX, STAR

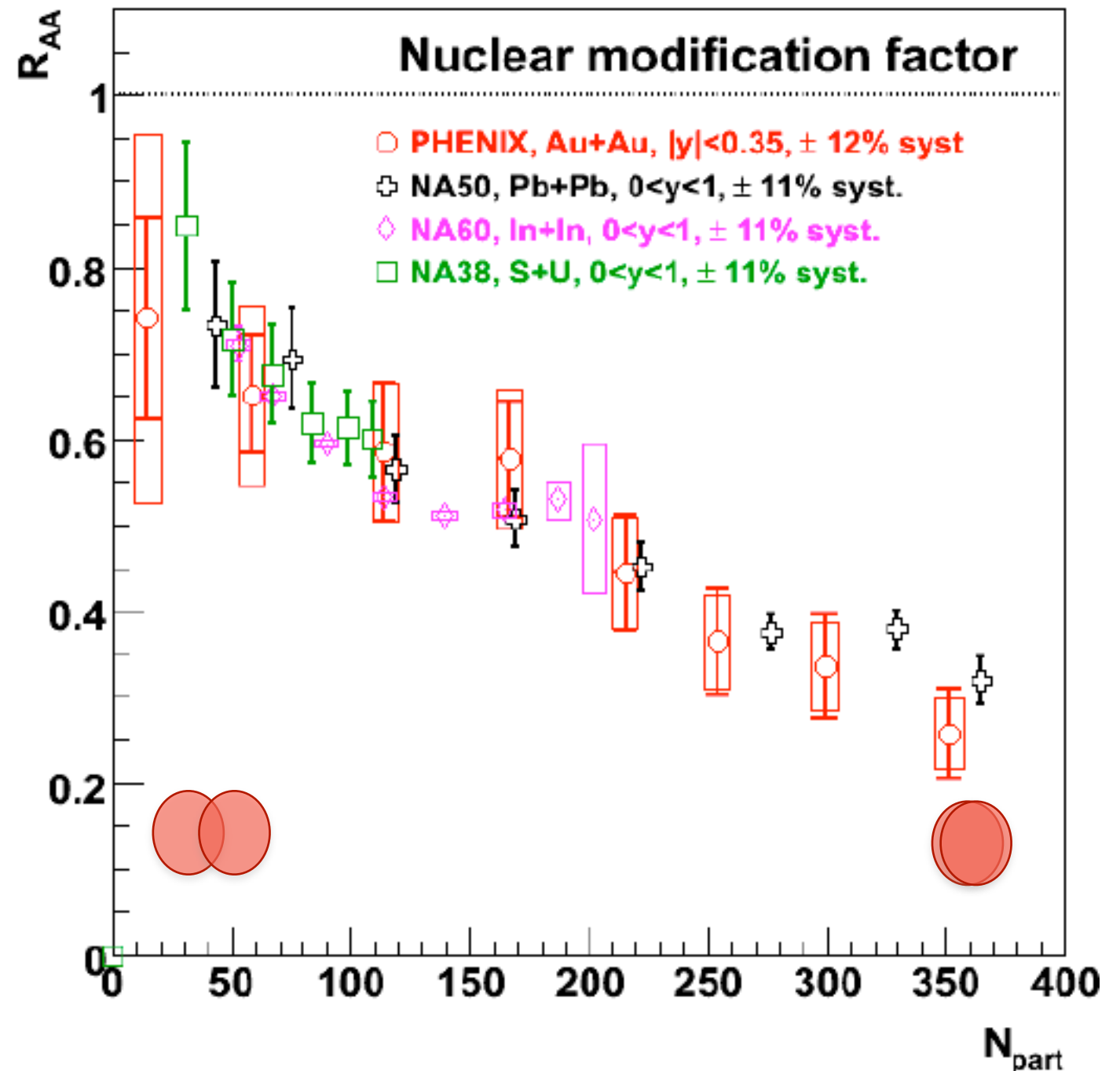
$\sqrt{s_{NN}} = 200$ GeV

Au-Au

J/ Ψ suppression increases with collision centrality

Similar R_{AA} at SPS and RHIC while energy density of formed QGP increases!

But cold nuclear matter effects differ with energy: estimate the CNM



Cold nuclear matter effect for J/Ψ

PHENIX Coll. PRL107 (2011) 142301

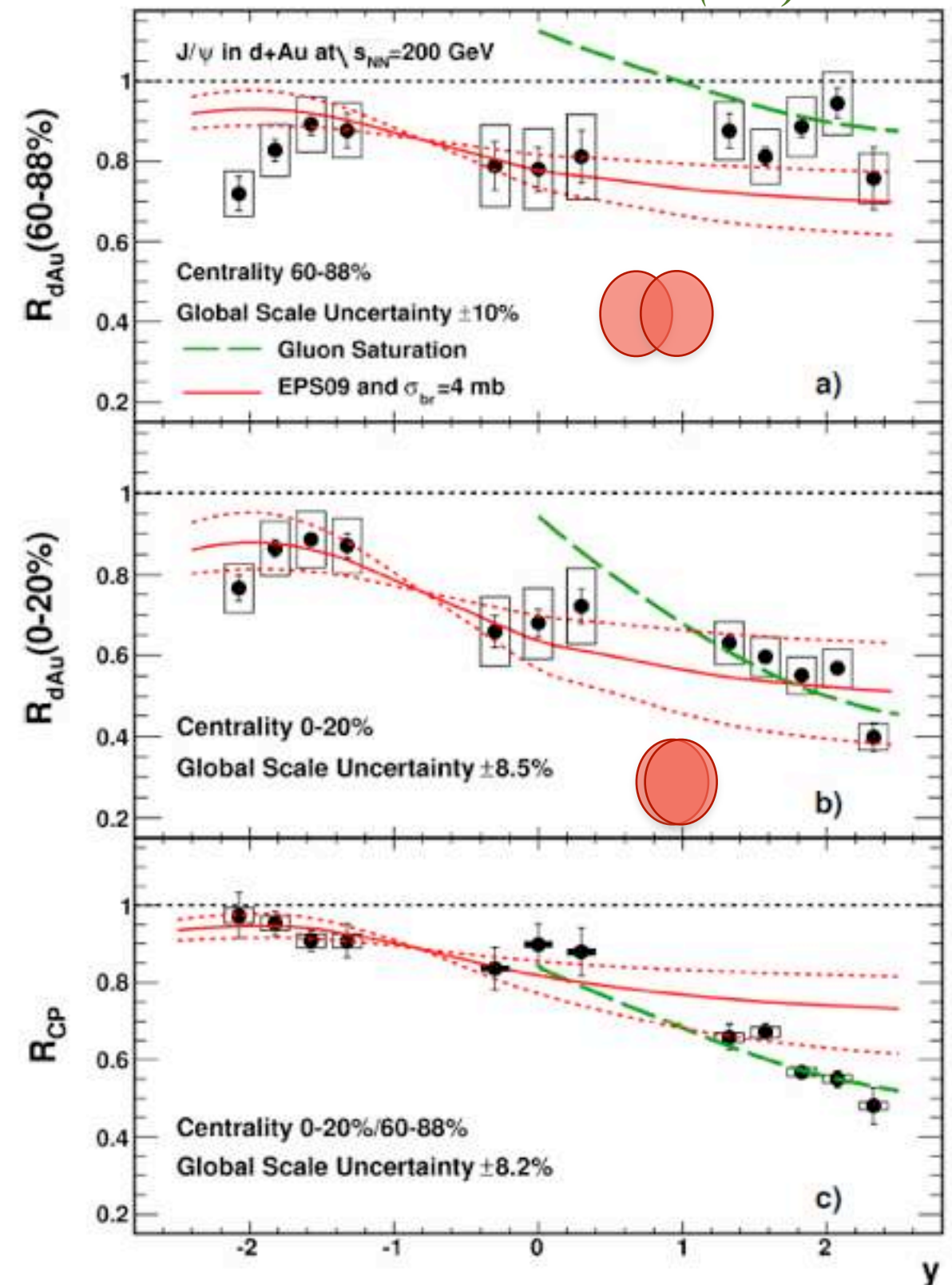
Cold nuclear matter effects estimated in d-Au @ 200 GeV (RHIC) or p-Pb @ 29 GeV and p-In @ 17 GeV (SPS)

J/Ψ suppressed in d-Au at 200 GeV

Less suppressed at backward and mid-rapidity than forward rapidity for most central collisions

Difficult to understand in terms of shadowing of parton distribution function (npdf) and single nuclear break-up cross-section: how to constrain the cold nuclear matter in a AA collisions?

Try some effective parametrization of CNM...



Results from SPS and RHIC

N. Brambilla et al., Eur.Phys.J. C71 (2011) 1534

SPS: NA50, NA60

$\sqrt{s_{NN}} = 17 \text{ GeV}$

In-In / Pb-Pb

$\sqrt{s_{NN}} = 19 \text{ GeV}$

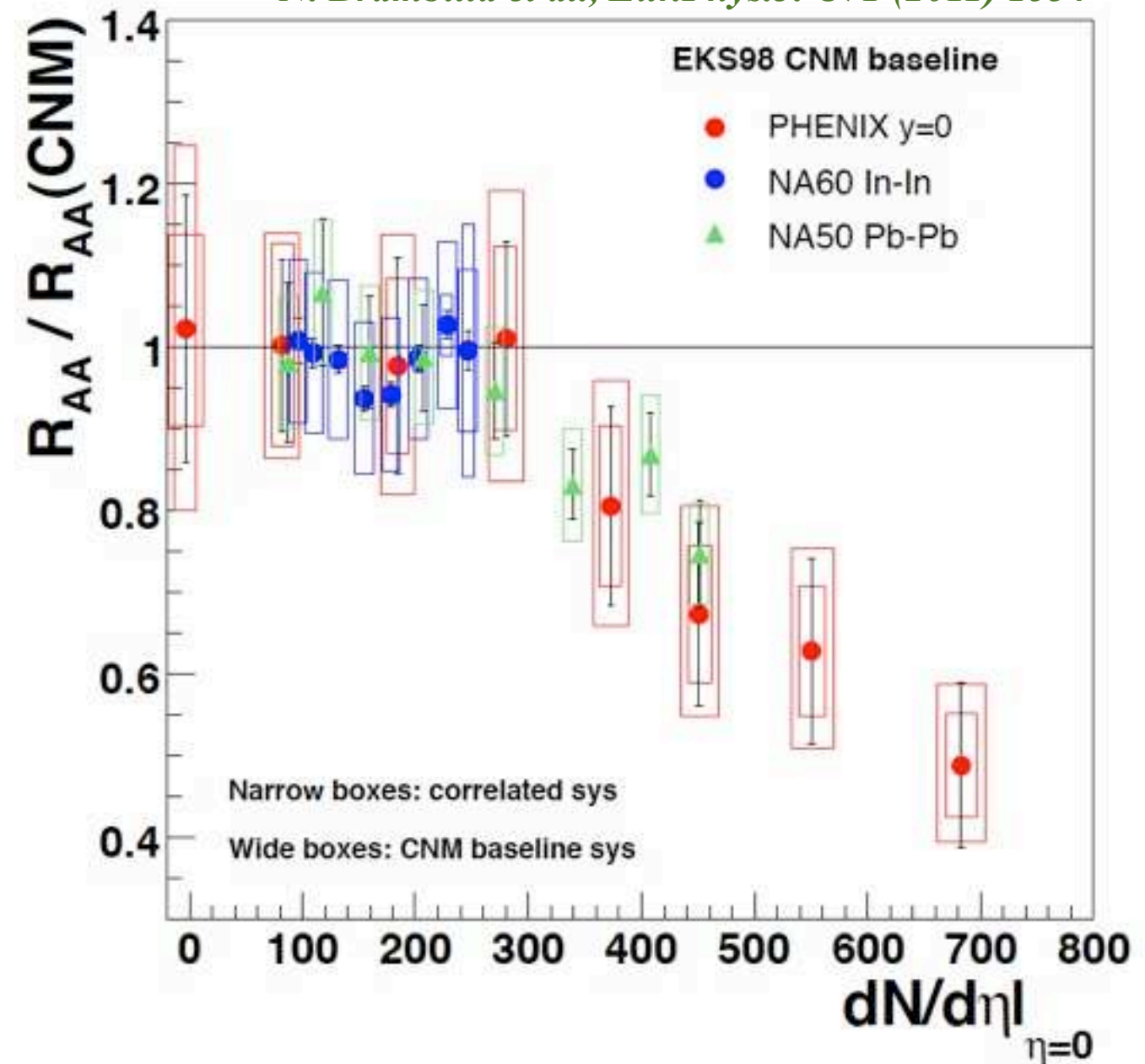
S-U

RHIC: PHENIX, STAR

$\sqrt{s_{NN}} = 200 \text{ GeV}$

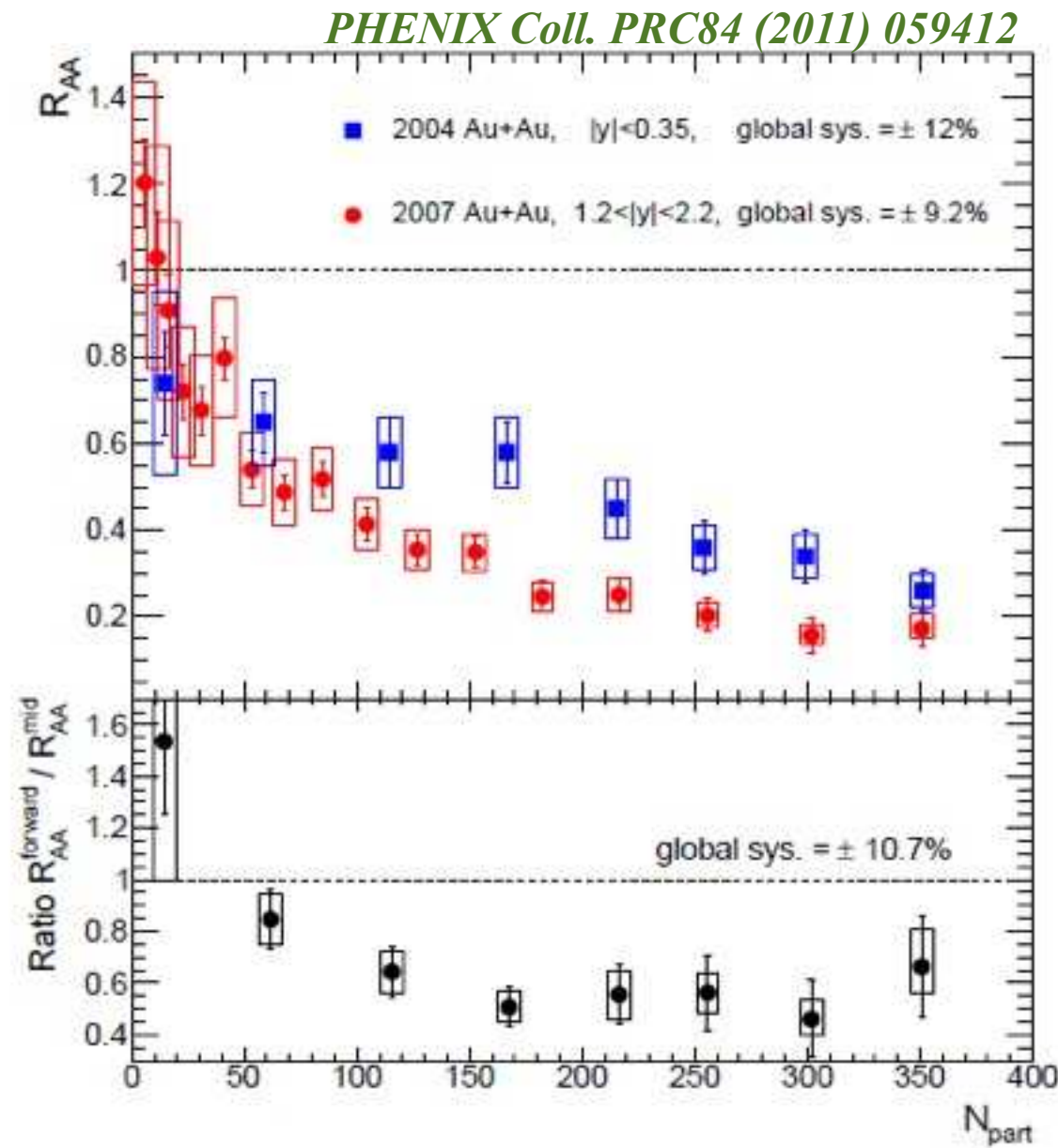
Au-Au

...and assuming that CNM effects factorize...



Anomalous J/Ψ suppression at SPS (up to 25%) and RHIC (up to 50%)
Similar suppression for a given multiplicity

y-dependence of J/Ψ R_{AA} at RHIC



More suppression (40%) at forward rapidity not expected (density of the QGP higher at mid-rapidity)

Cold nuclear matter effect: R_{dAu} is lower at forward y ?

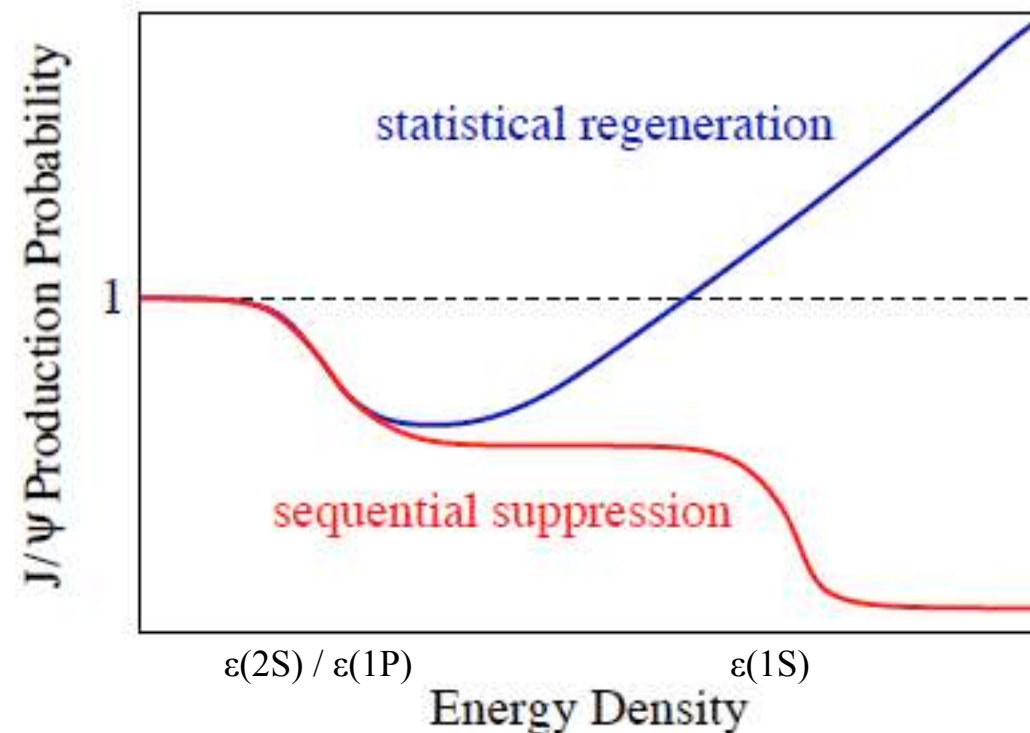
Another mechanism: J/Ψ regeneration?

Secondary J/Ψ production?

Enhancement of J/Ψ in a QGP

c and cbar combination at the hadronization stage:
J/Ψ regeneration

Expected if total charm cross-section is large



Total charm production at RHIC

$\sigma_{ccbar} \approx 1 \text{ mb @ } 200 \text{ GeV} = 2\% \text{ of the hadronic cross-section}$

→ 20 pairs of ccbar created in Au-Au @ 200 GeV for most central collisions

Regeneration implies:

- Evidence of thermalization of charm quarks
- J/Ψ and Ψ(2S) not anymore a QGP thermometer
- Not expected for bottomonium

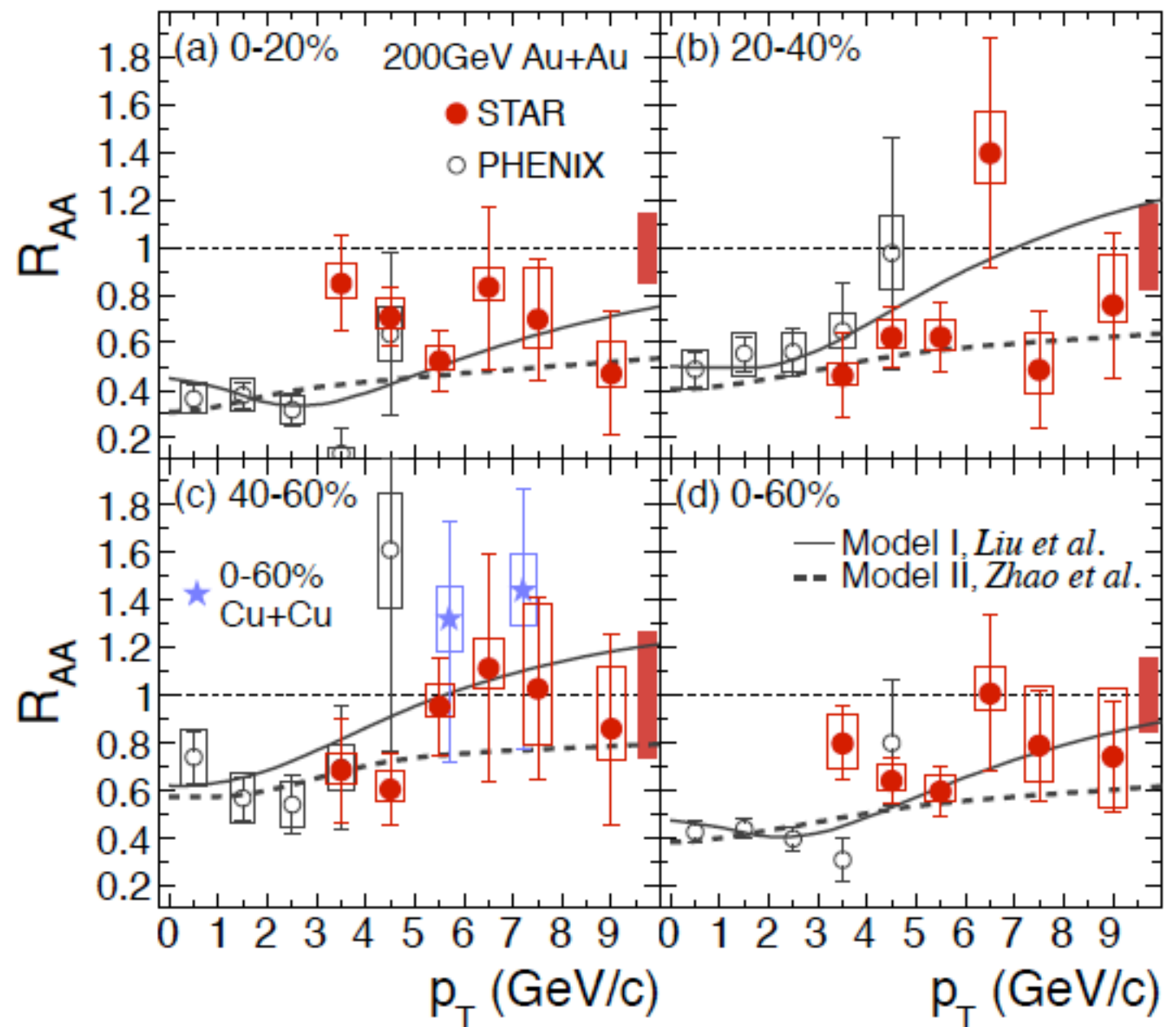
p_T dependence of J/Ψ R_{AA} at RHIC

At large p_T :
 No recombination possible
 Cold nuclear matter as initial state
 effect expected to be negligible

Less suppression at large p_T
 But still suppression of 40% for most
 central collisions at $p_T > 5$ GeV/c
 p_T dependence not easily understood
 with color screening and npdfs

Be aware that this is for inclusive J/Ψ
 while B feed-down contribution is
 important at large p_T

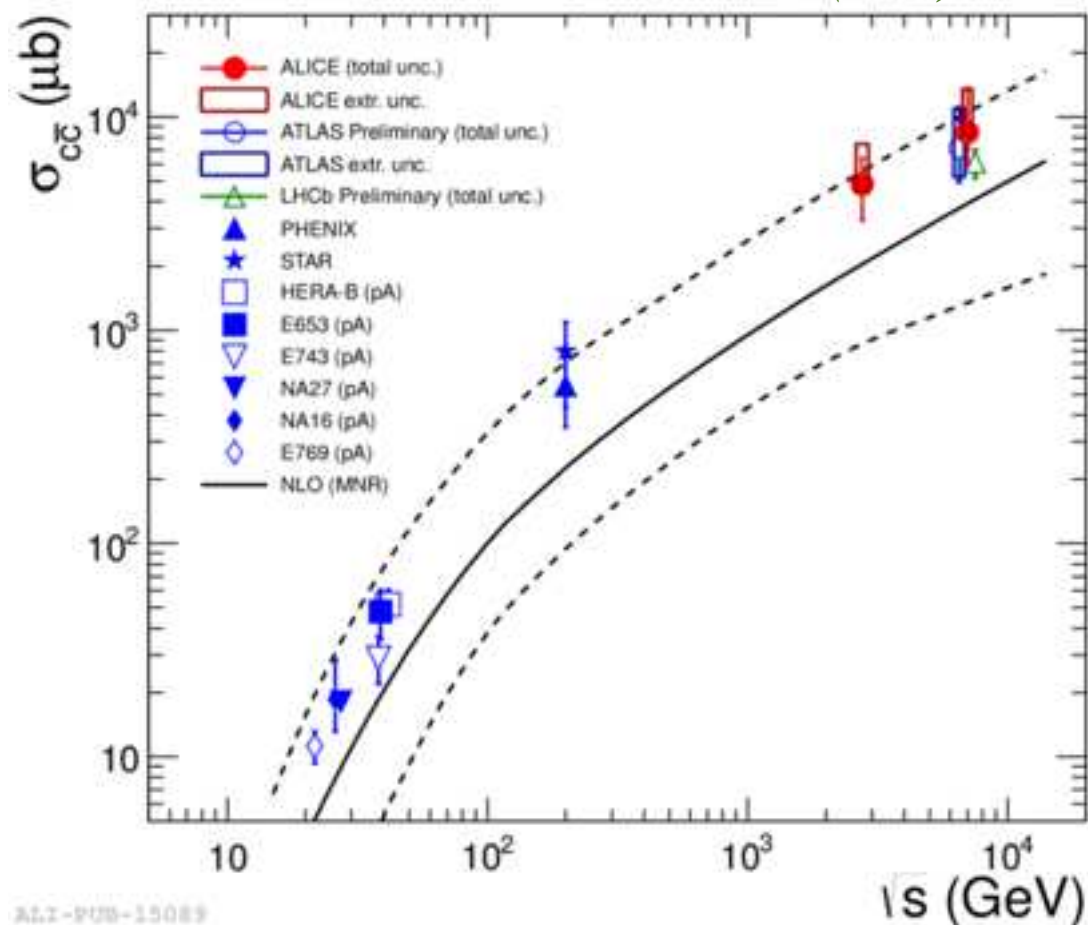
STAR Coll. arXiv:1208.2736



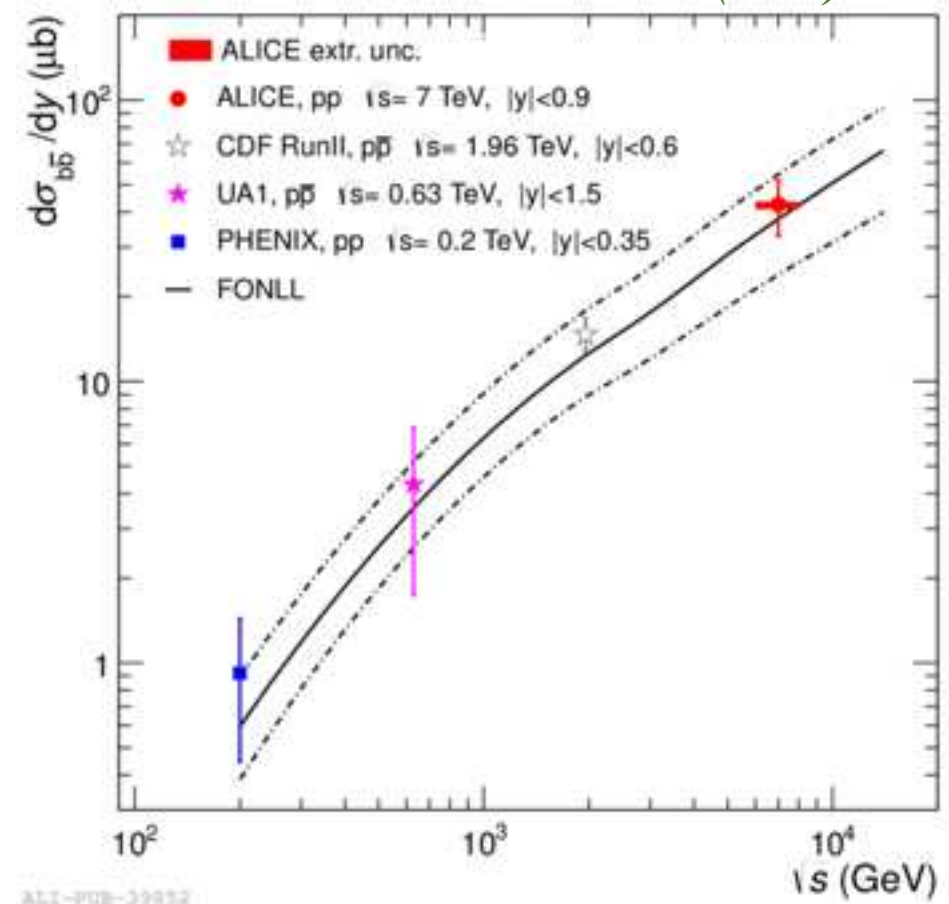
Results from LHC

LHC 10 x higher energy than RHIC: higher rates for open and hidden heavy flavour production

ALICE Coll. JHEP 1207 (2012) 191



ALICE Coll. JHEP 11 (2012) 065

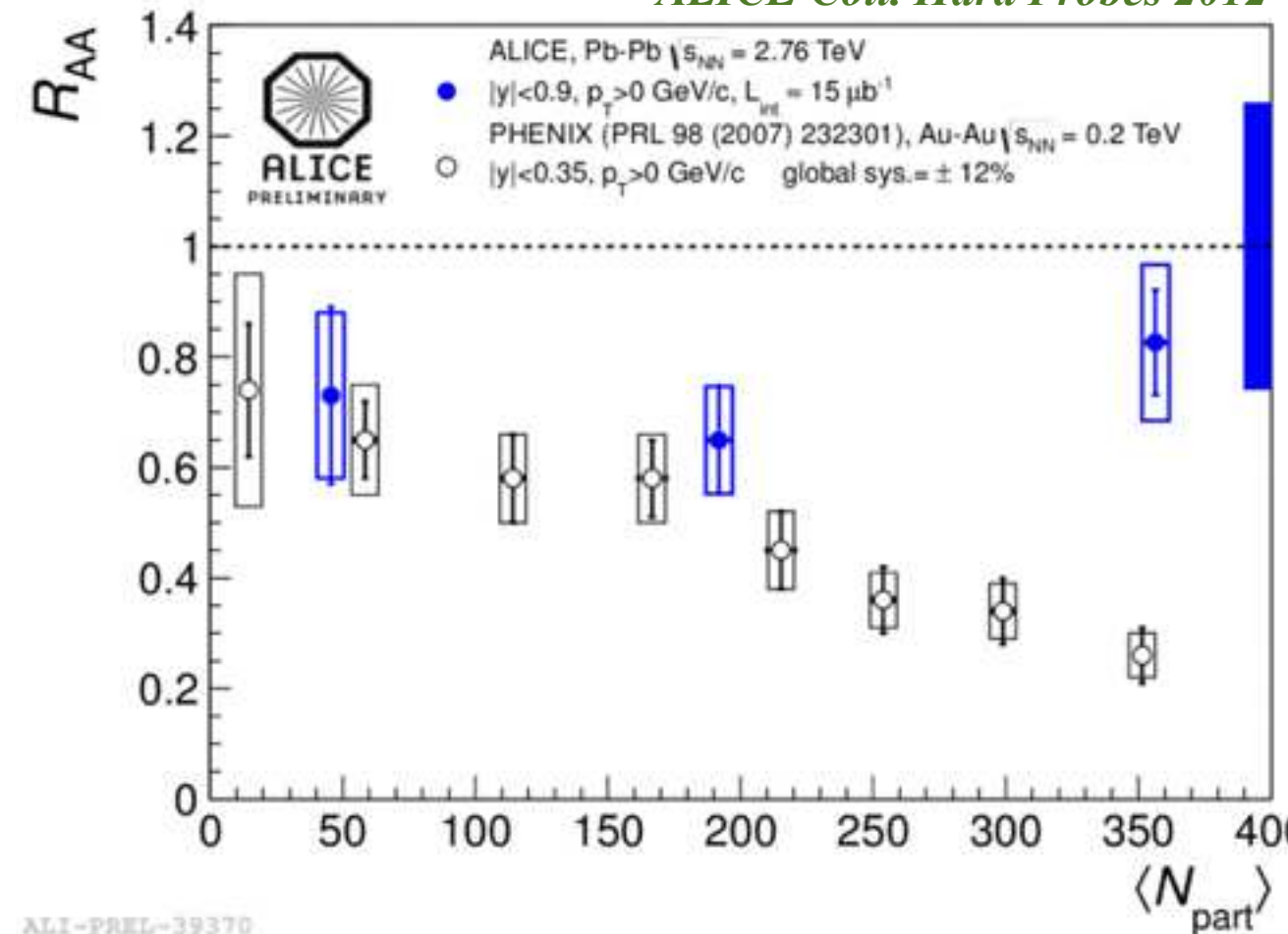


LHC $\sigma_{c\bar{c}} \approx 5 \text{ mb} @ 2.76 \text{ TeV} = 7\%$ of the hadronic x-section
 \rightarrow 115 pairs of $c\bar{c}$ created in Pb-Pb @ 2.76 TeV for most central collisions

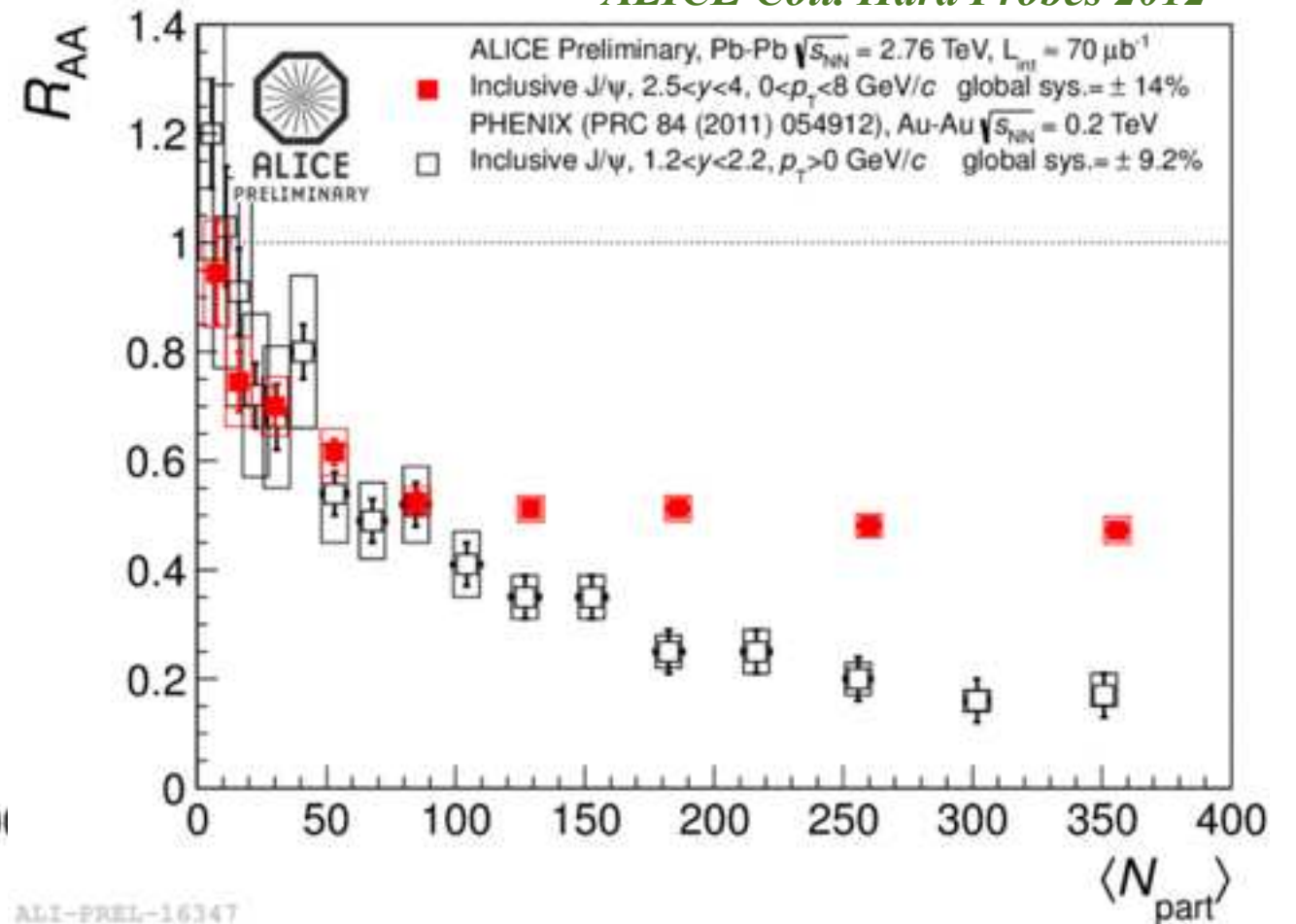
If regeneration of J/Ψ already at RHIC, a higher contribution is expected at LHC

J/Ψ R_{AA} vs centrality

ALICE Coll. Hard Probes 2012



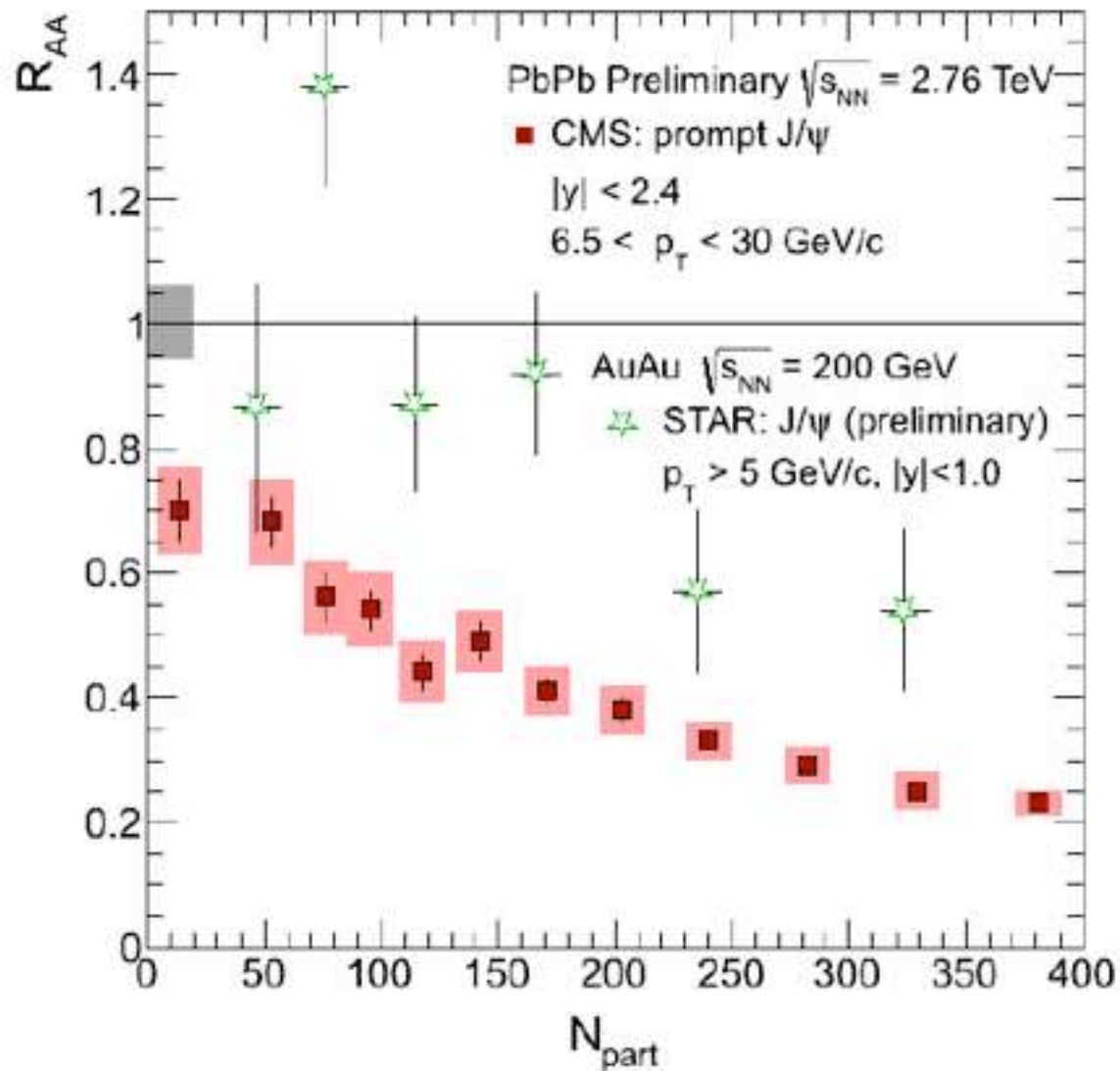
ALICE Coll. Hard Probes 2012



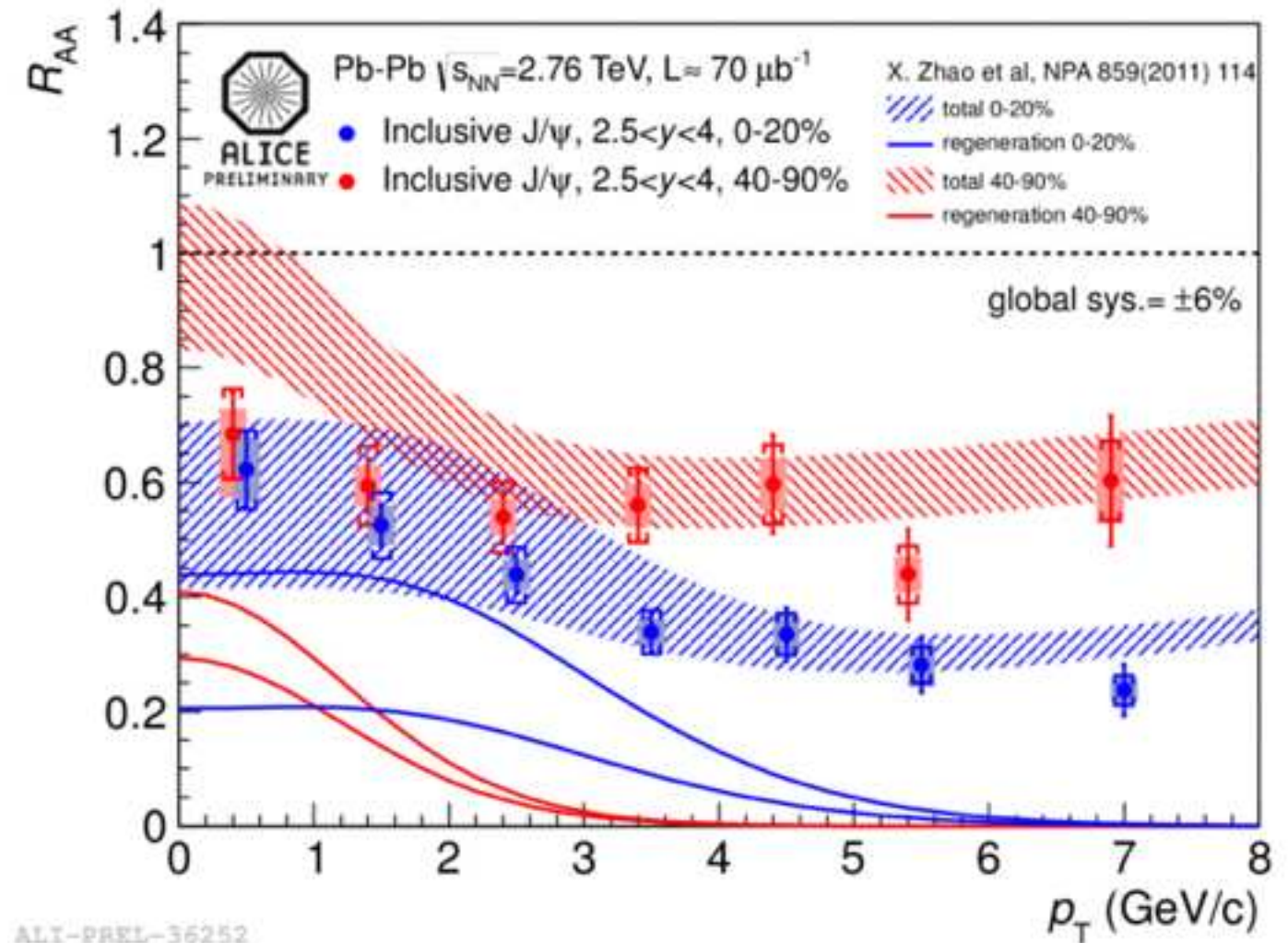
J/Ψ R_{AA} larger at LHC than at RHIC at mid- and forward (for $N_{part} > 100$) rapidity for most central collisions
 → consistent with regeneration mechanism

J/Ψ R_{AA} for high p_T and vs p_T

CMS-PAS-HIN-12-014



ALICE Coll. QM 2012



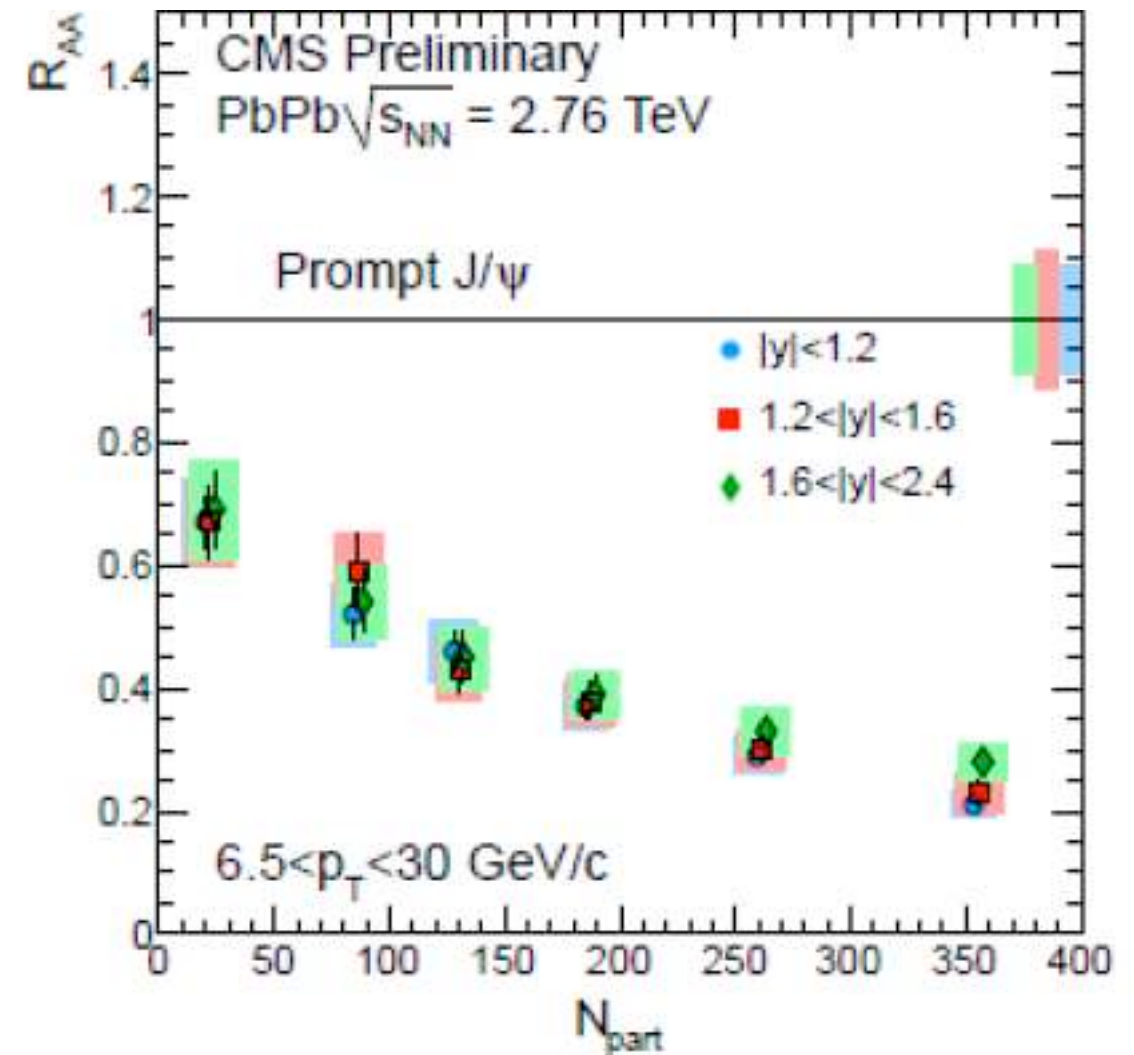
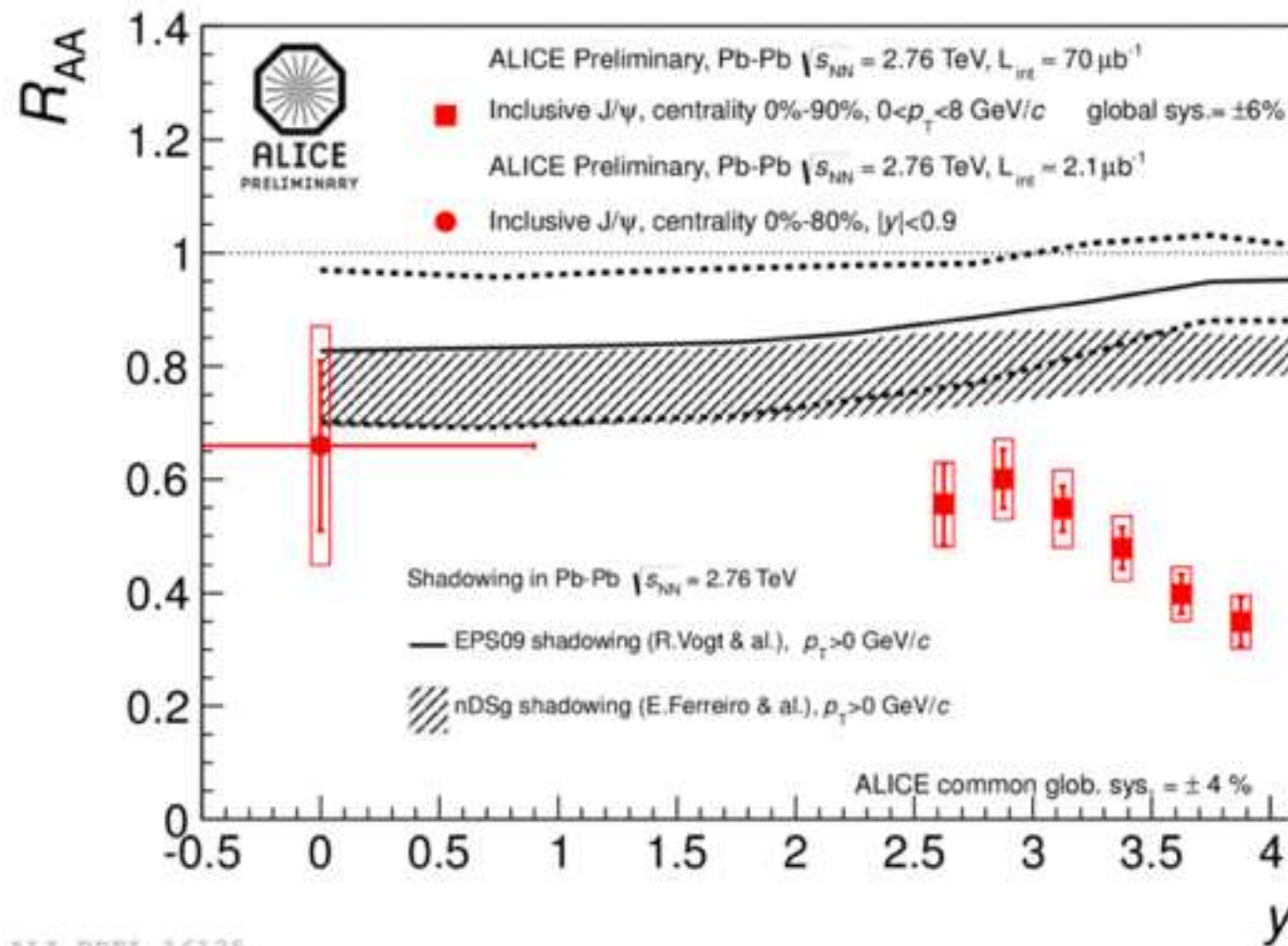
At large p_T , J/Ψ R_{AA} lower at LHC than at RHIC as expected if color screening mechanism only in a QGP

J/Ψ less suppressed at low p_T than high p_T for most central collisions

J/Ψ R_{AA} vs y

CMS-PAS-HIN-12-014

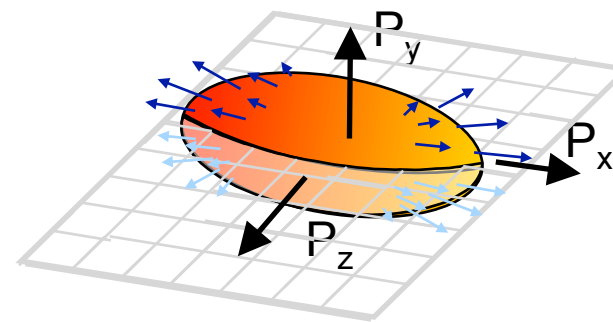
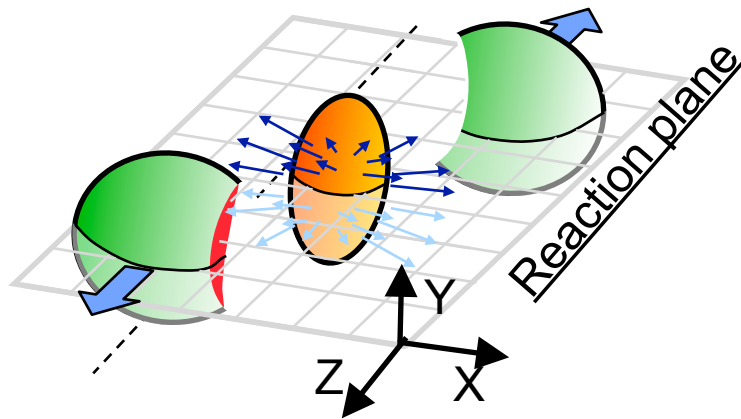
ALICE Coll. Hard Probes 2012



J/Ψ more suppressed at forward rapidity if integrated over p_T
 Shadowing models do not account for this rapidity decrease of R_{AA}
 No or small rapidity dependence for large p_T

Elliptic flow

In nuclei collisions at **finite impact parameter**: anisotropy of the **geometrical overlap region**
 For **interacting matter** (via multiple collisions): spatial asymmetry → **anisotropy of the particle momentum distribution**



Azimuthal dependence of the particle yield

$$E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)] \right)$$

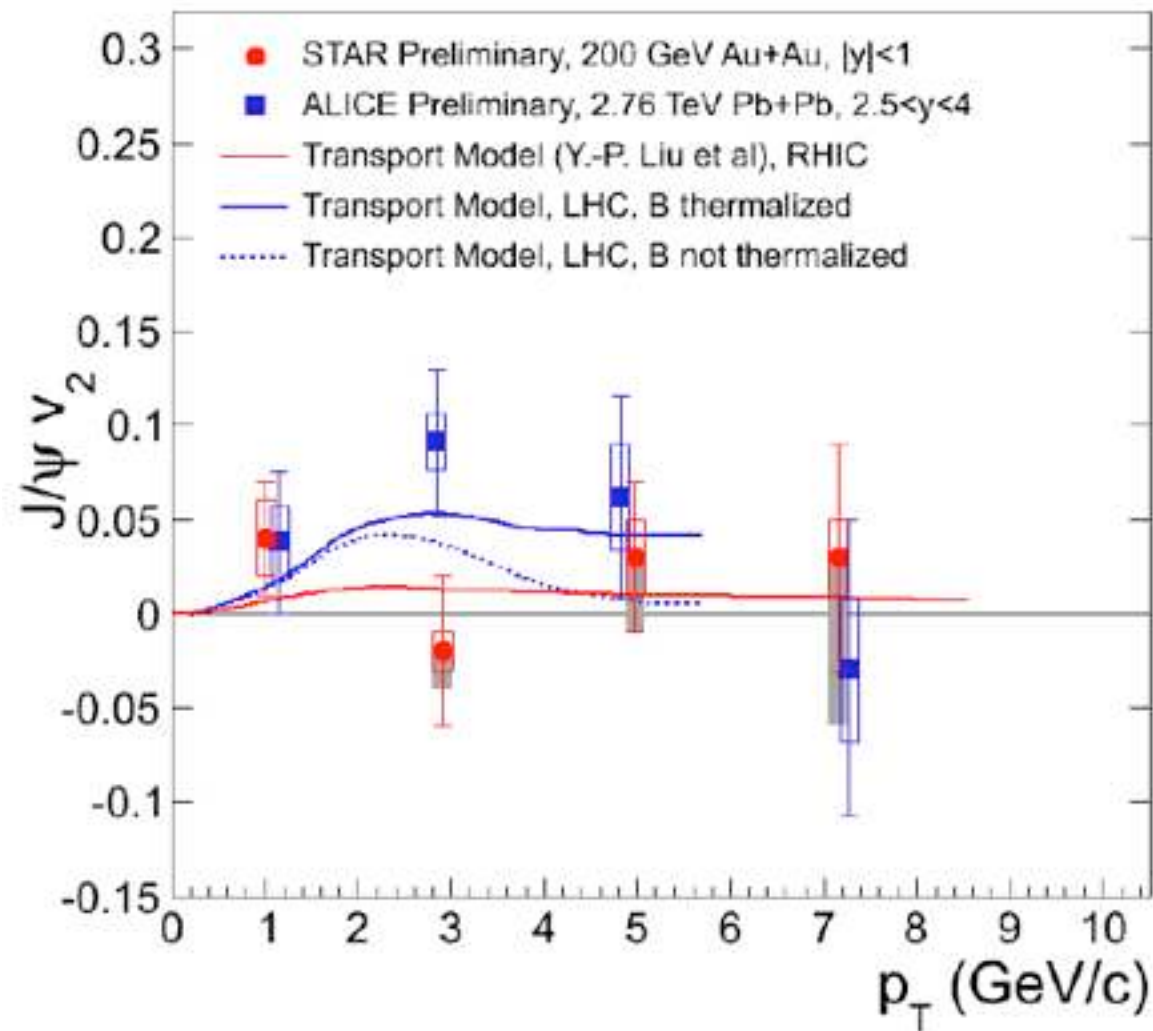
Elliptic flow $n=2$
 $v_2(p_T) = \langle \cos(2\phi) \rangle(p_T)$

If c quarks participate to the collective motion of the QGP, then
 they will acquire some elliptic flow
 Regenerated J/ψ will inherit their elliptic flow

J/Ψ elliptic flow

ALICE Coll., Hard Probes 2012

STAR Coll, JPG38, 124107 (2011)



Flow compatible with zero measured by STAR (RHIC)

Non-zero J/psi v_2 observed at intermediate p_T for semi-central collisions at LHC

v_2 and R_{AA} at low p_T qualitatively described by models including regeneration

First $\Psi(2S)$ measurements

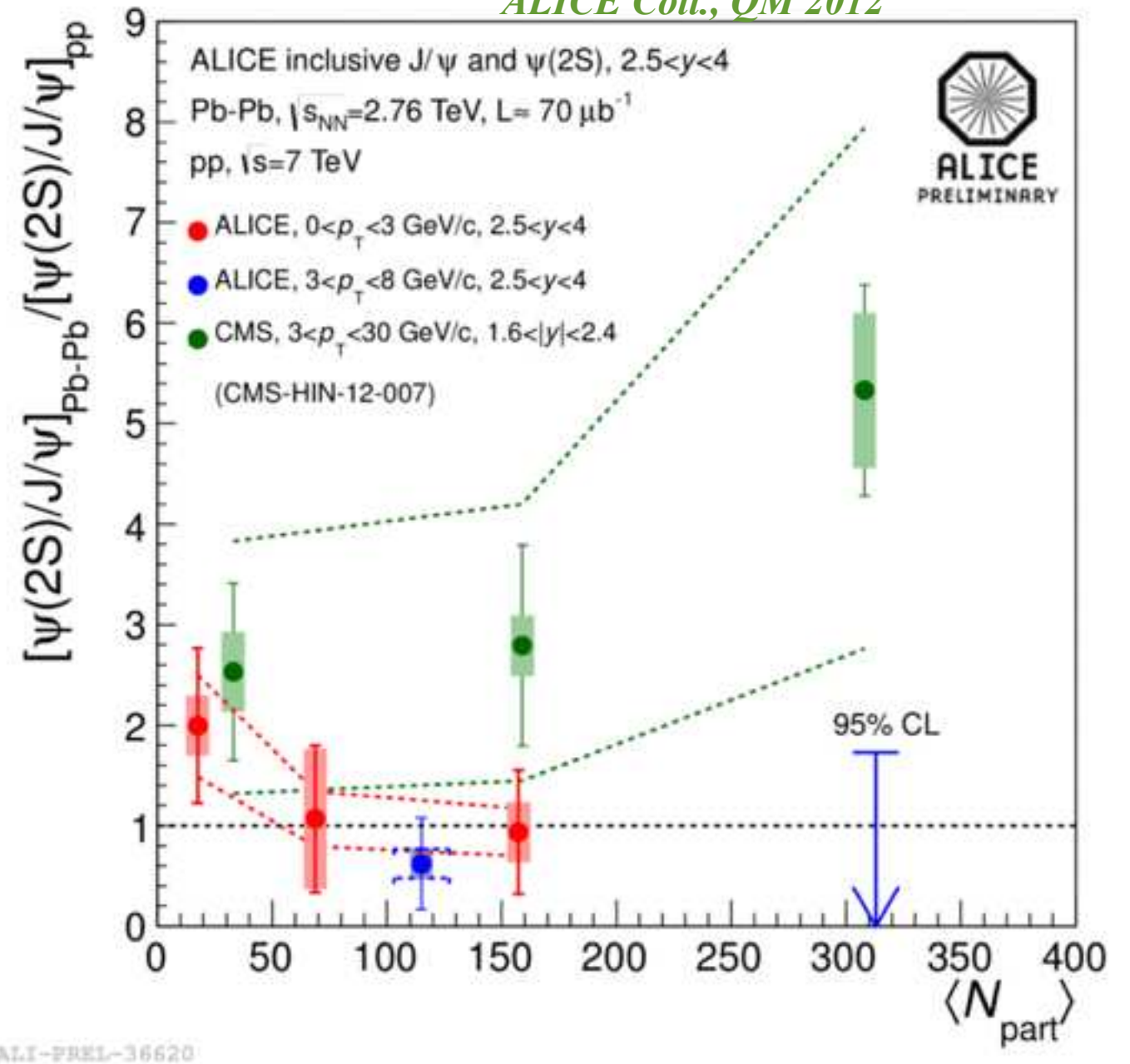
CMS Coll., Hard Probes 2012

ALICE Coll., QM 2012

Double ratio measurement:
 $\Psi(2S)/J/\Psi$ in Pb-Pb over p-p

CMS measures a $\Psi(2S)$ enhancement
wrt J/Ψ for $p_T > 3$ GeV/c

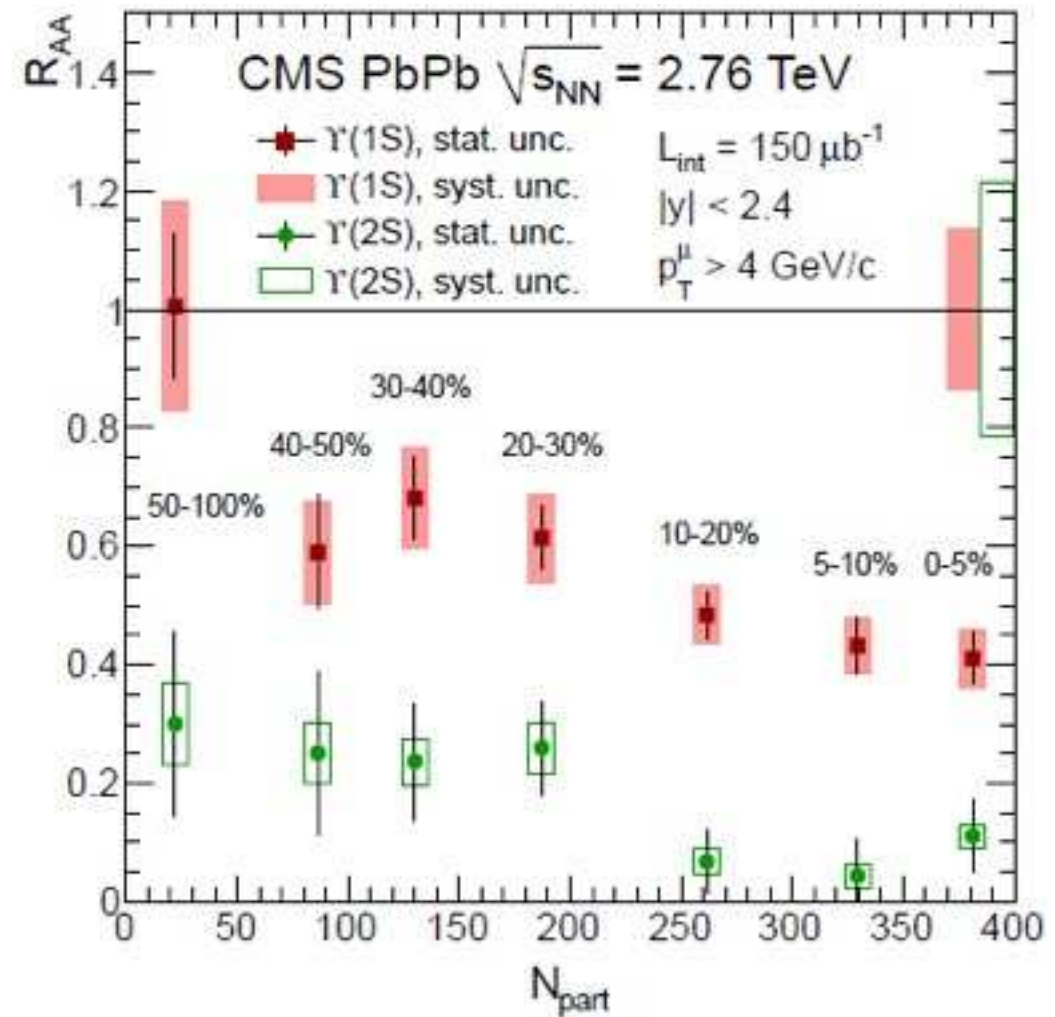
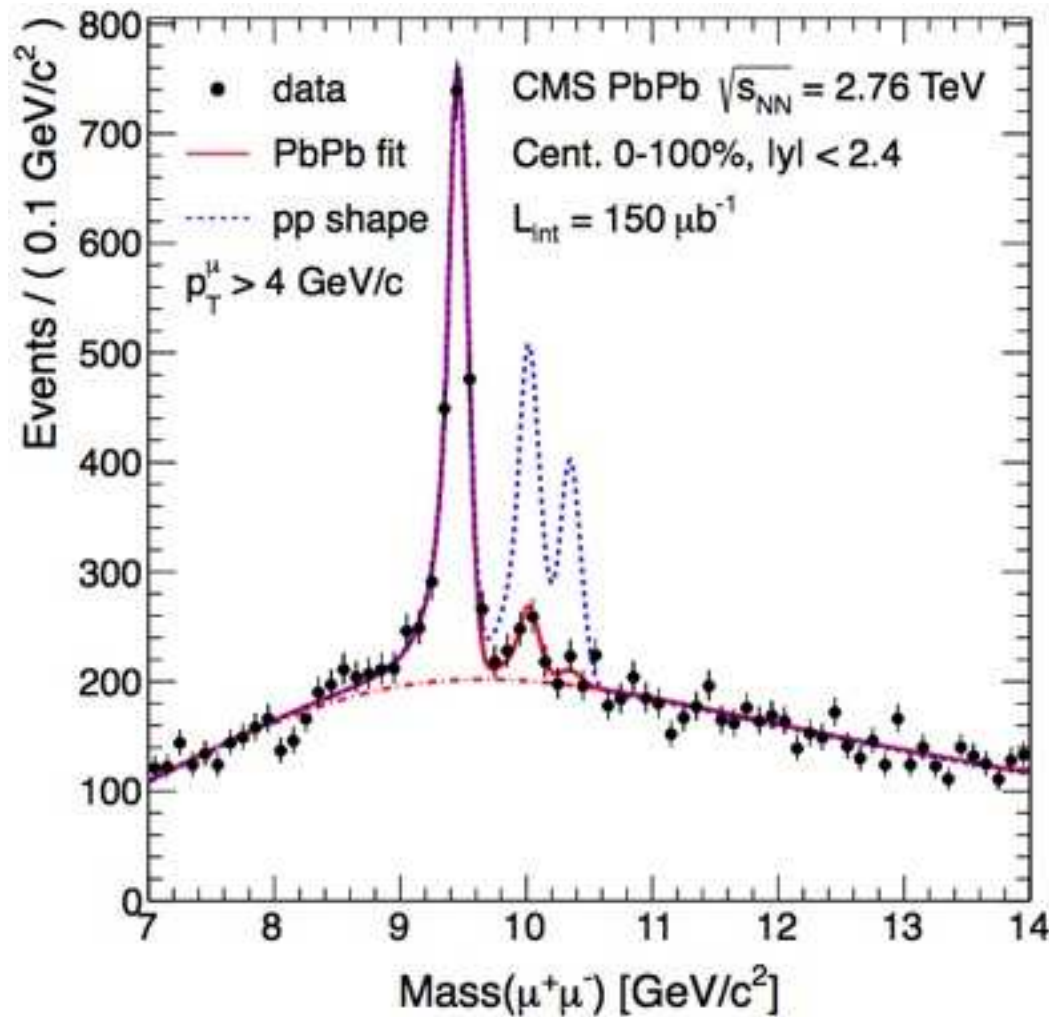
ALICE does not measure a sign of
large $\Psi(2S)$ enhancement



Both data are compatible: large uncertainties due to low statistics at $p_T > 3$ GeV/c
and lack of solid pp reference at 2.76 TeV

Bottomonium family

CMS Coll. PRL 109 (2012) 222301



STAR Coll. QM 2012

Y(3s) completely melted
Y(2s) strongly suppressed
Y(1S) suppression consistent with
excited states suppression by color
screening

RHIC: $R_{AA}(\Upsilon(1S+2S+3S)) = 0.56 \pm 0.21 + 0.08 - 0.16$

LHC: $R_{AA}(\Upsilon(1S+2S+3S)) \sim 0.32$

→ R_{AA} lower at RHIC than LHC

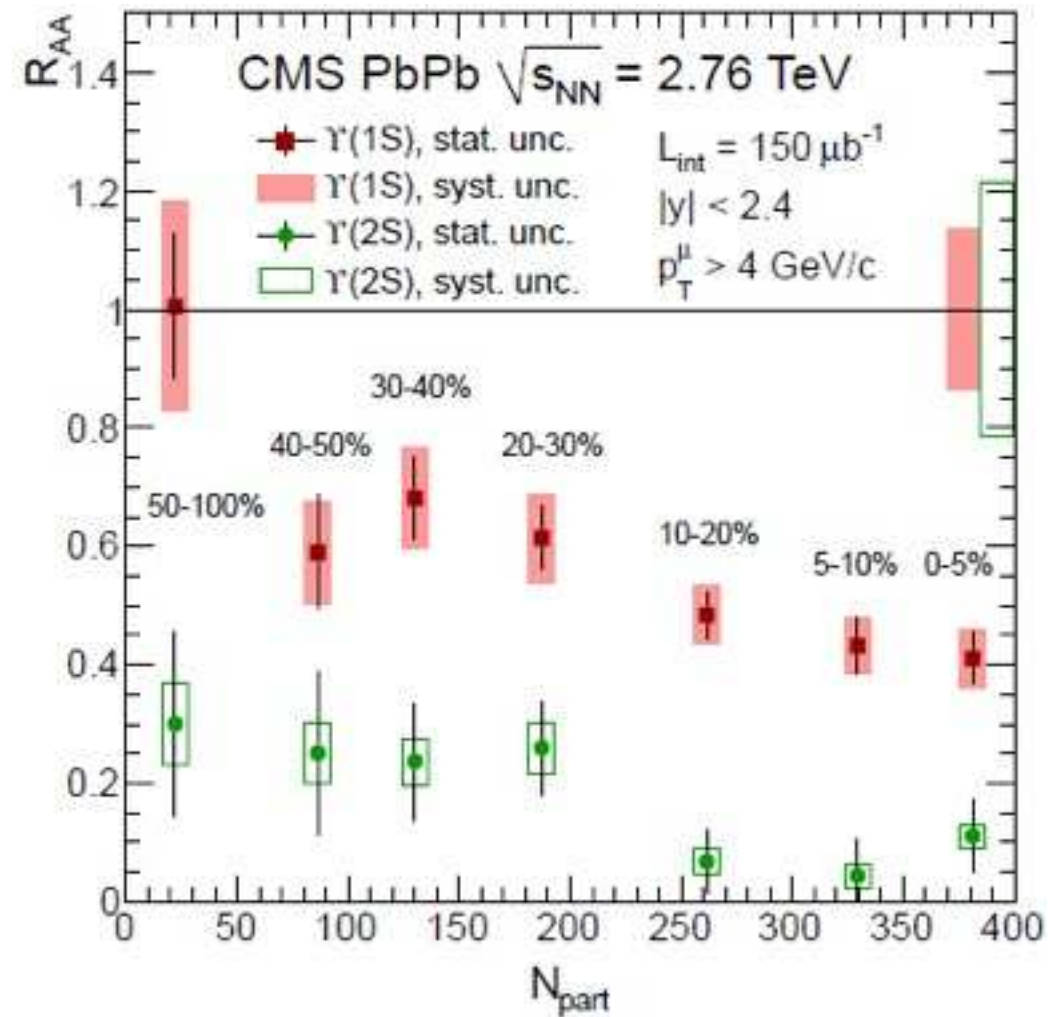
Bottomonium family

CMS Coll. PRL 109 (2012) 222301

$$\Upsilon(1S): R_{AA} = 0.56 \pm 0.08 + 0.07$$

$$\Upsilon(2S): R_{AA} = 0.12 \pm 0.04 + 0.02$$

$$\Upsilon(3S): R_{AA} < 0.10 \text{ (95\% CL)}$$



STAR Coll. QM 2012

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Conclusion and outlooks

SPS and RHIC data point out for an anomalous J/Ψ suppression by color screening but the rapidity dependence of R_{AA} gives a more complexe picture

At LHC, J/Ψ low p_T and flow measurements with ALICE is consistent with the mechanism of charm and anti-charm regeneration at the hadronization stage

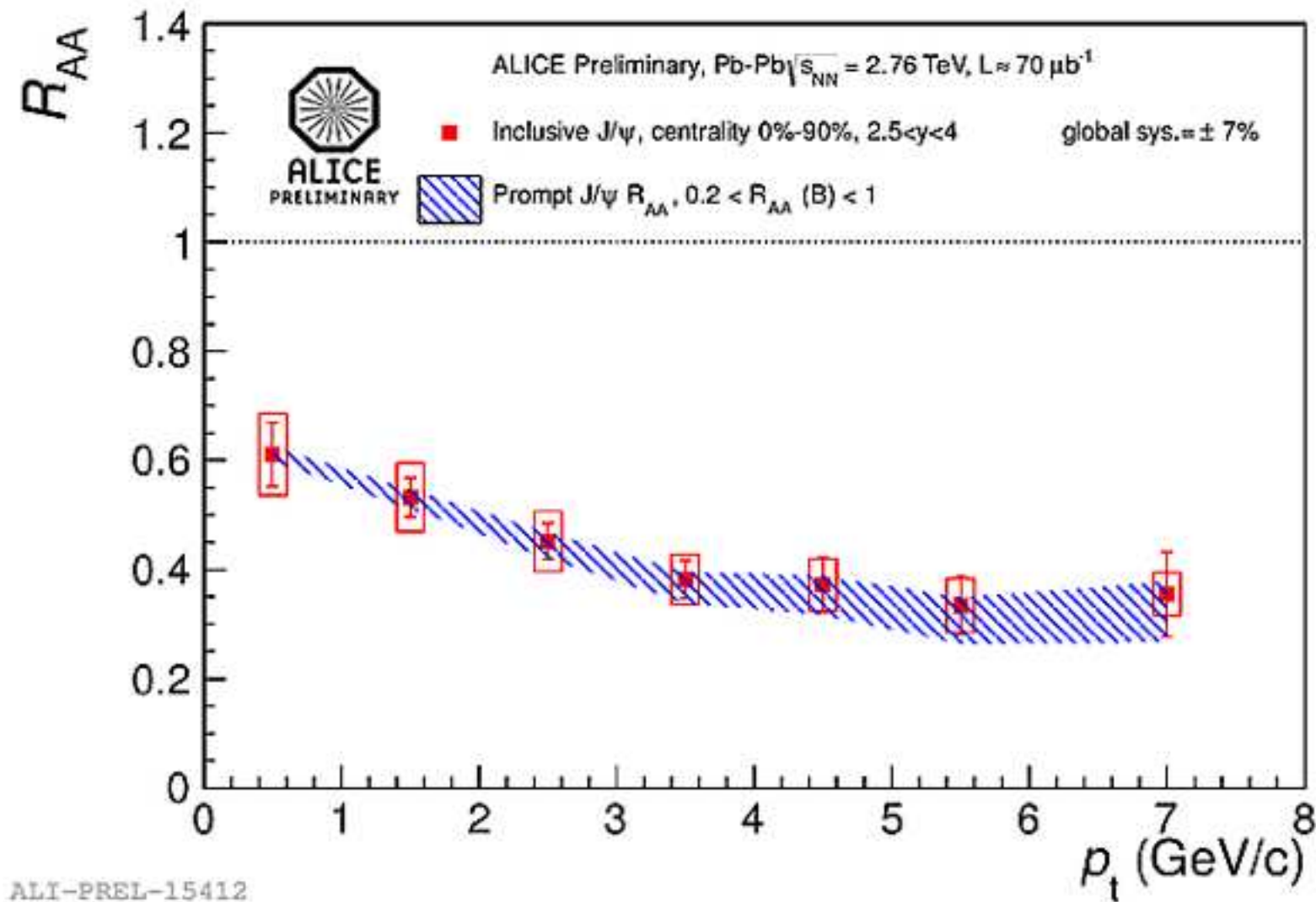
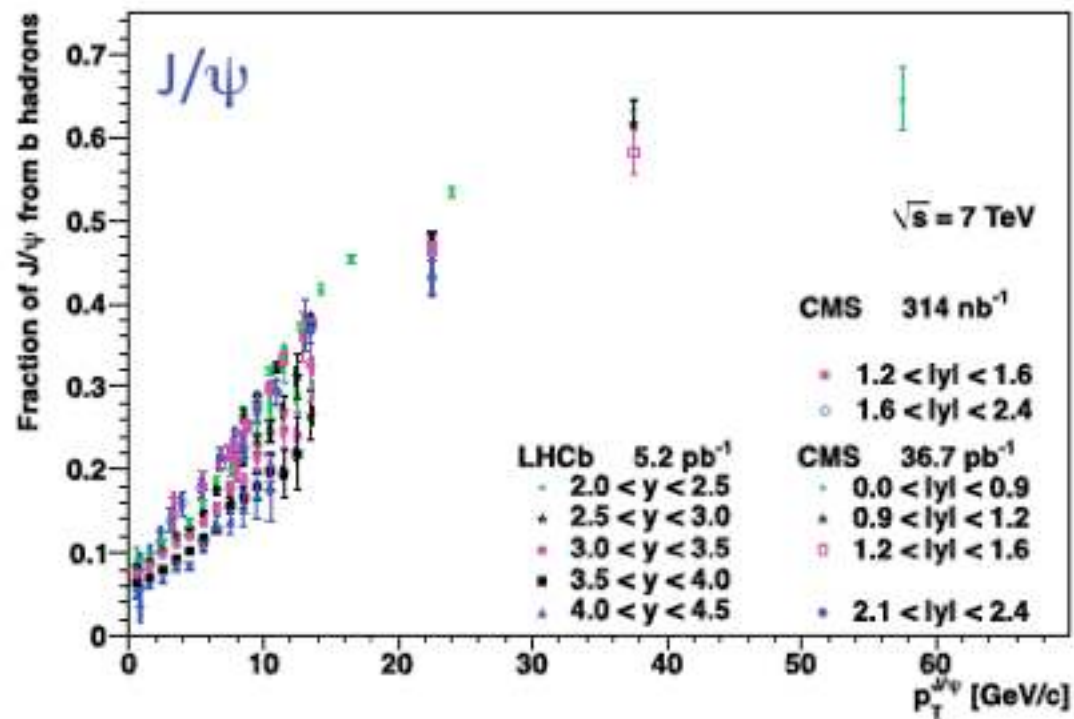
J/Ψ high p_T measured by ALICE and CMS are more suppressed than RHIC data

Upsilon suppression measured at CMS is compatible with sequential suppression of excited states

p-Pb results for charmonia and bottomonia production needed at LHC to disentangle hot and cold nuclear effects in Pb-Pb, to confirm these conclusions and to allow quantitative conclusions on the hot nuclear medium formed: p-Pb analysis ongoing

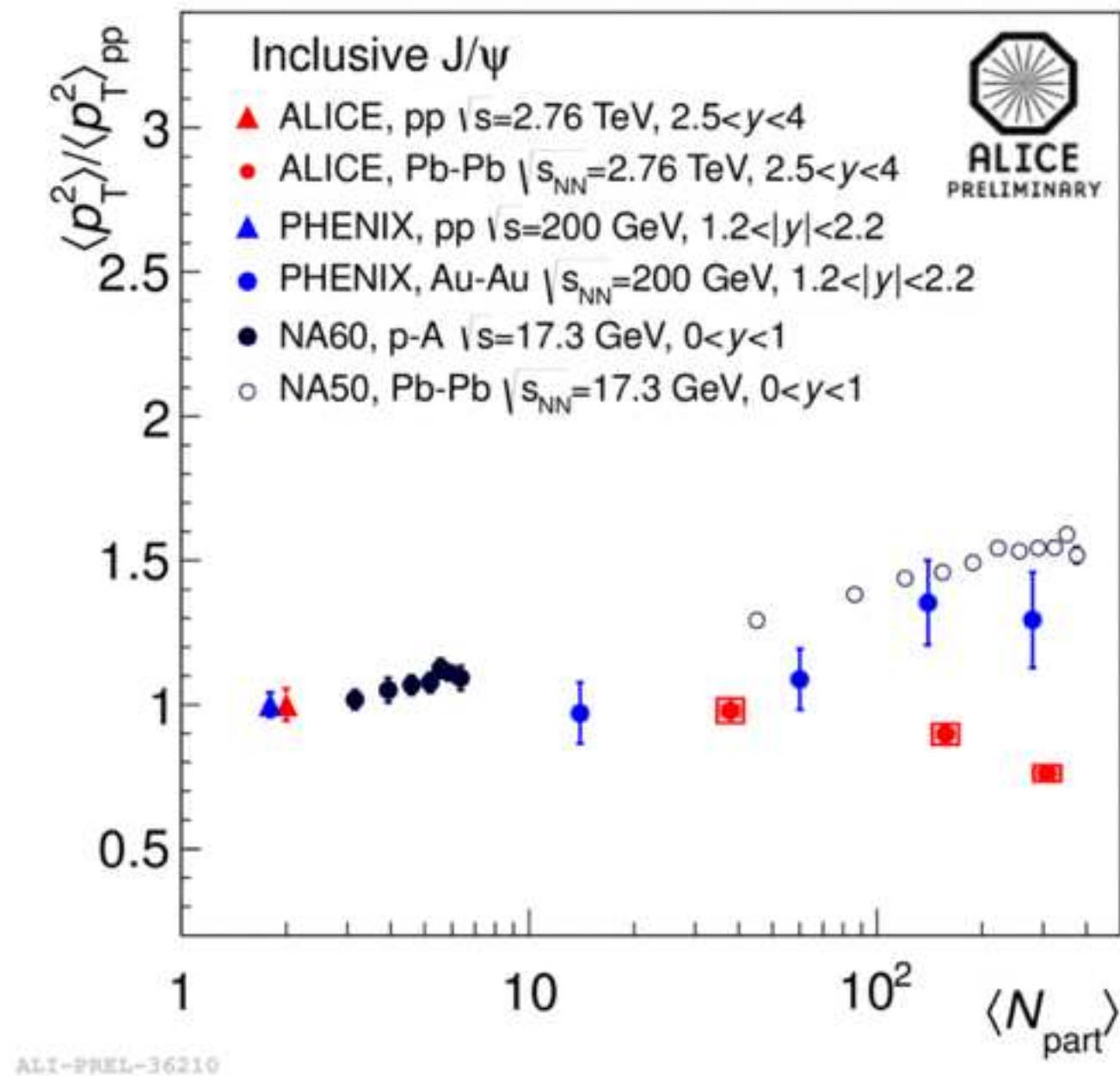
back-up slides

From inclusive to prompt J/ψ R_{AA}

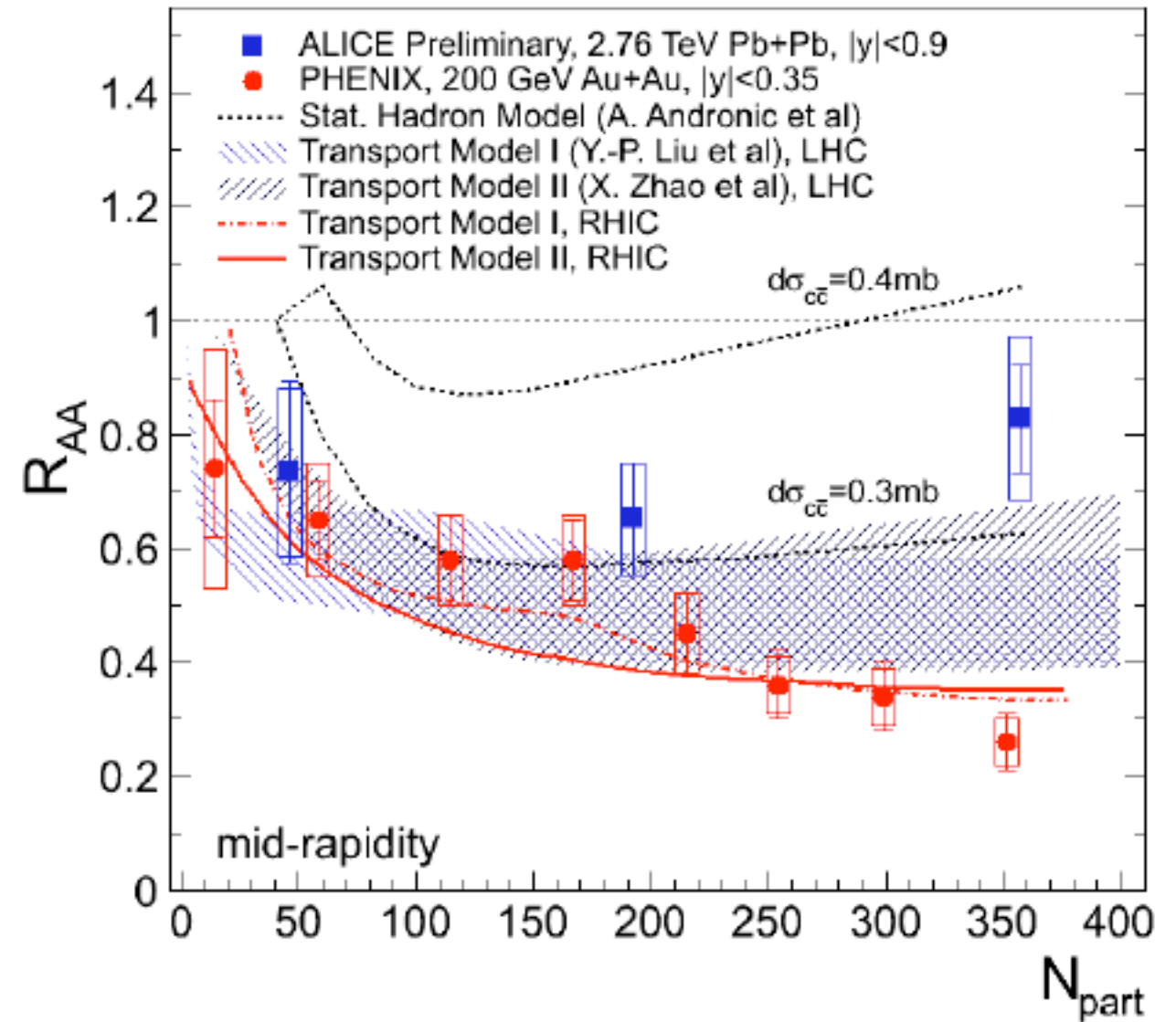
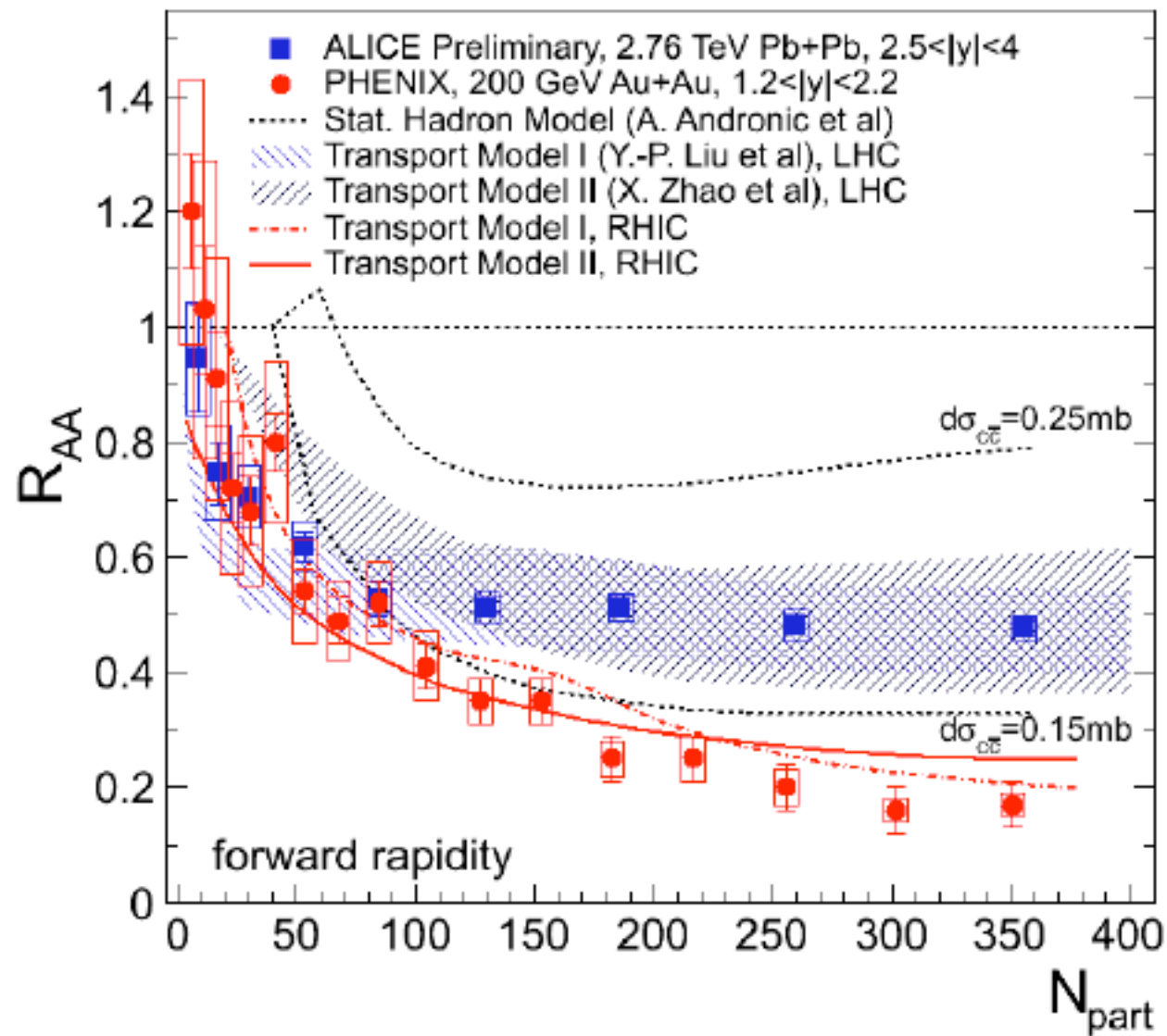


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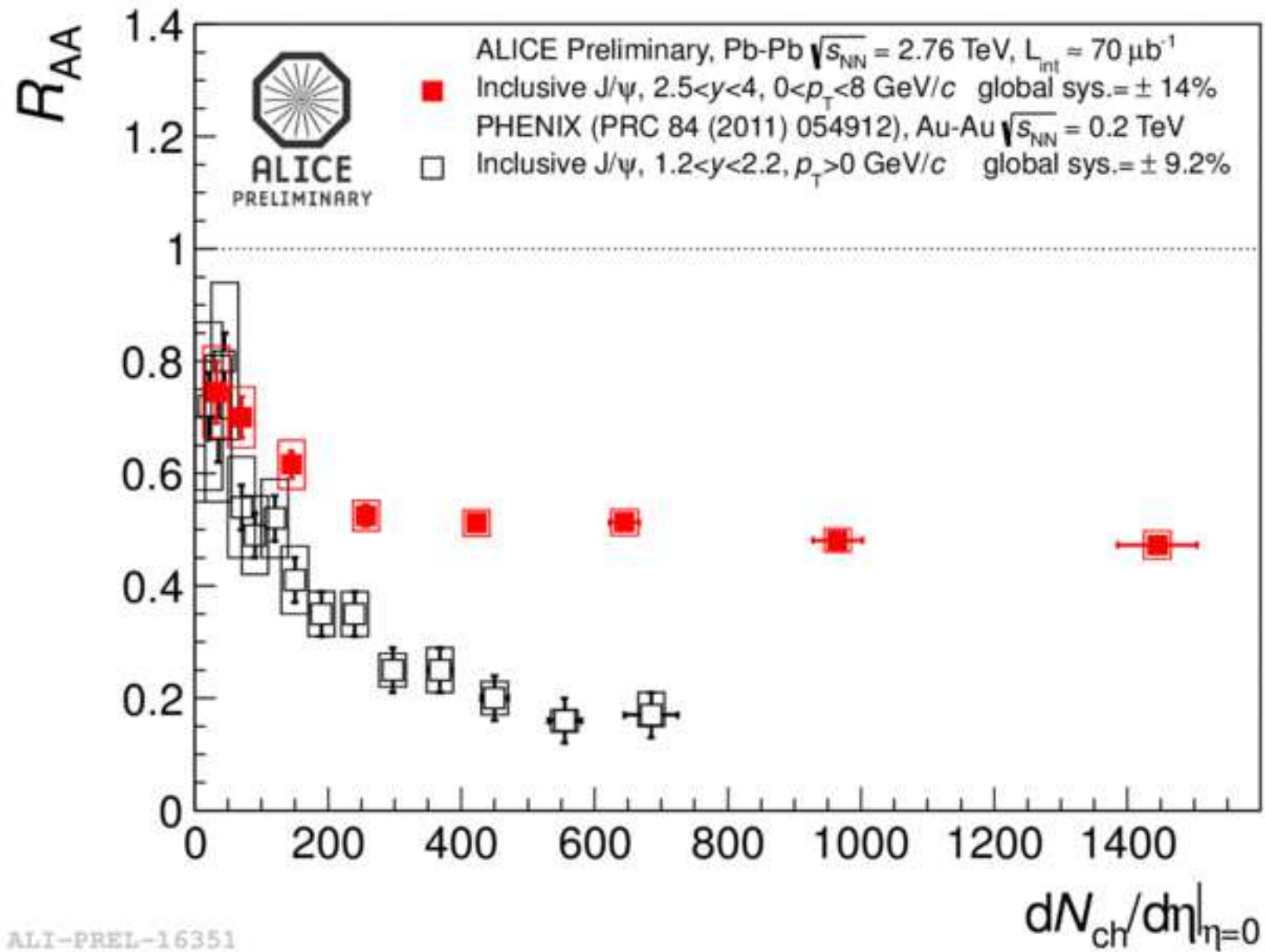
Inclusive J/Ψ $\langle p_T \rangle$



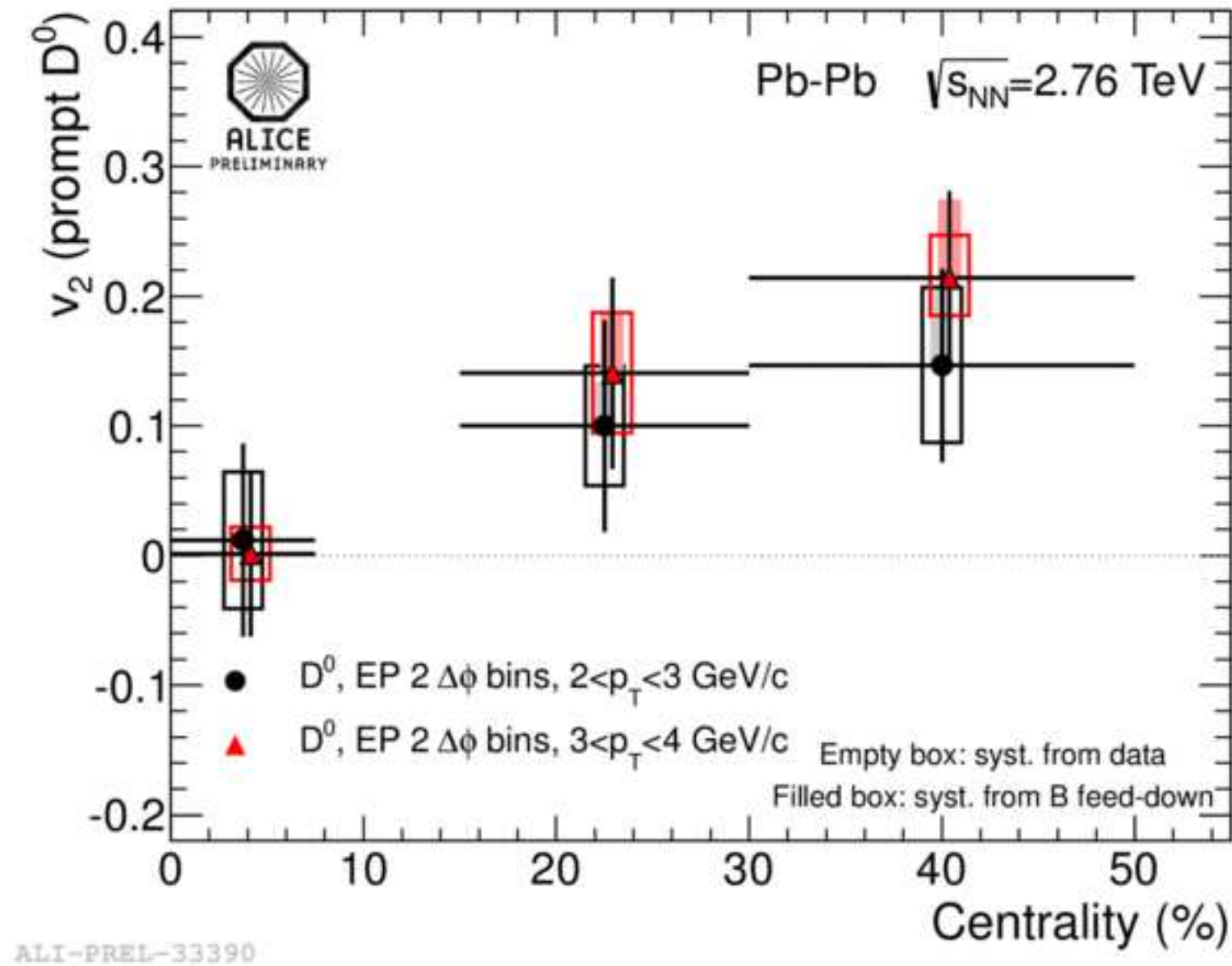
J/Ψ R_{AA} @ LHC and RHIC vs. models



LHC vs RHIC

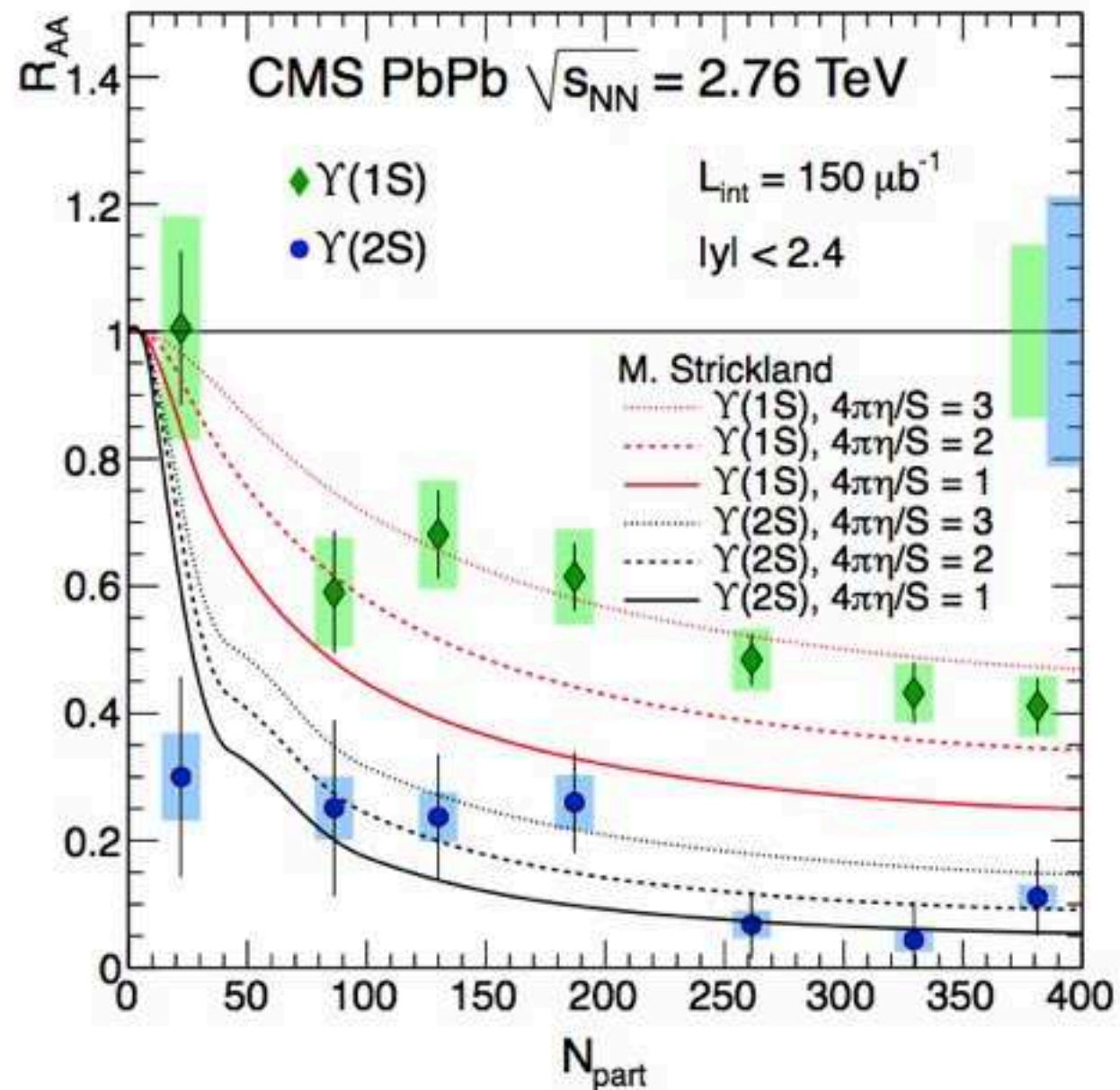


prompt D^0 v_2

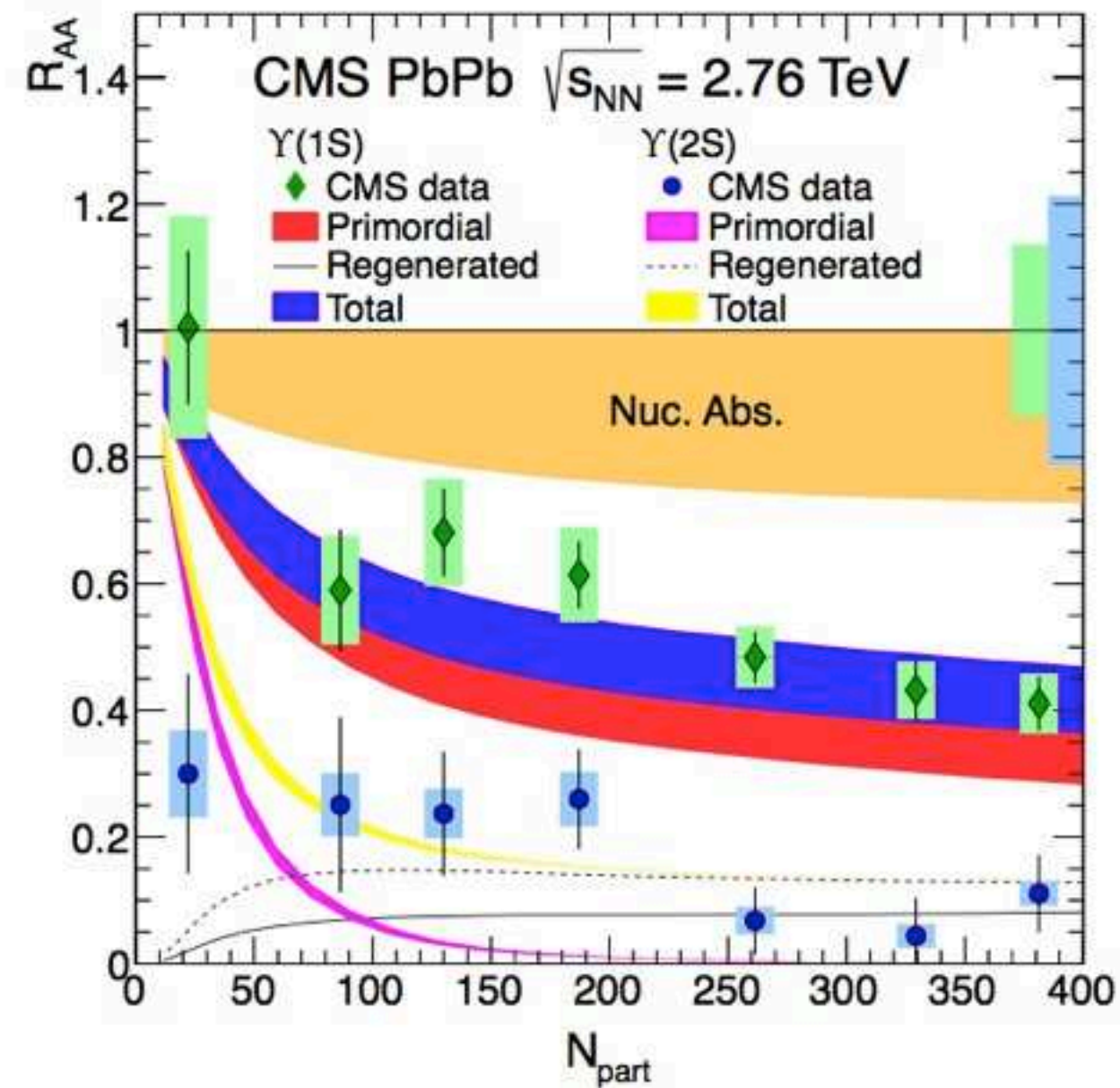


ΥR_{AA} @ LHC vs. models

arXiv:1208.2826

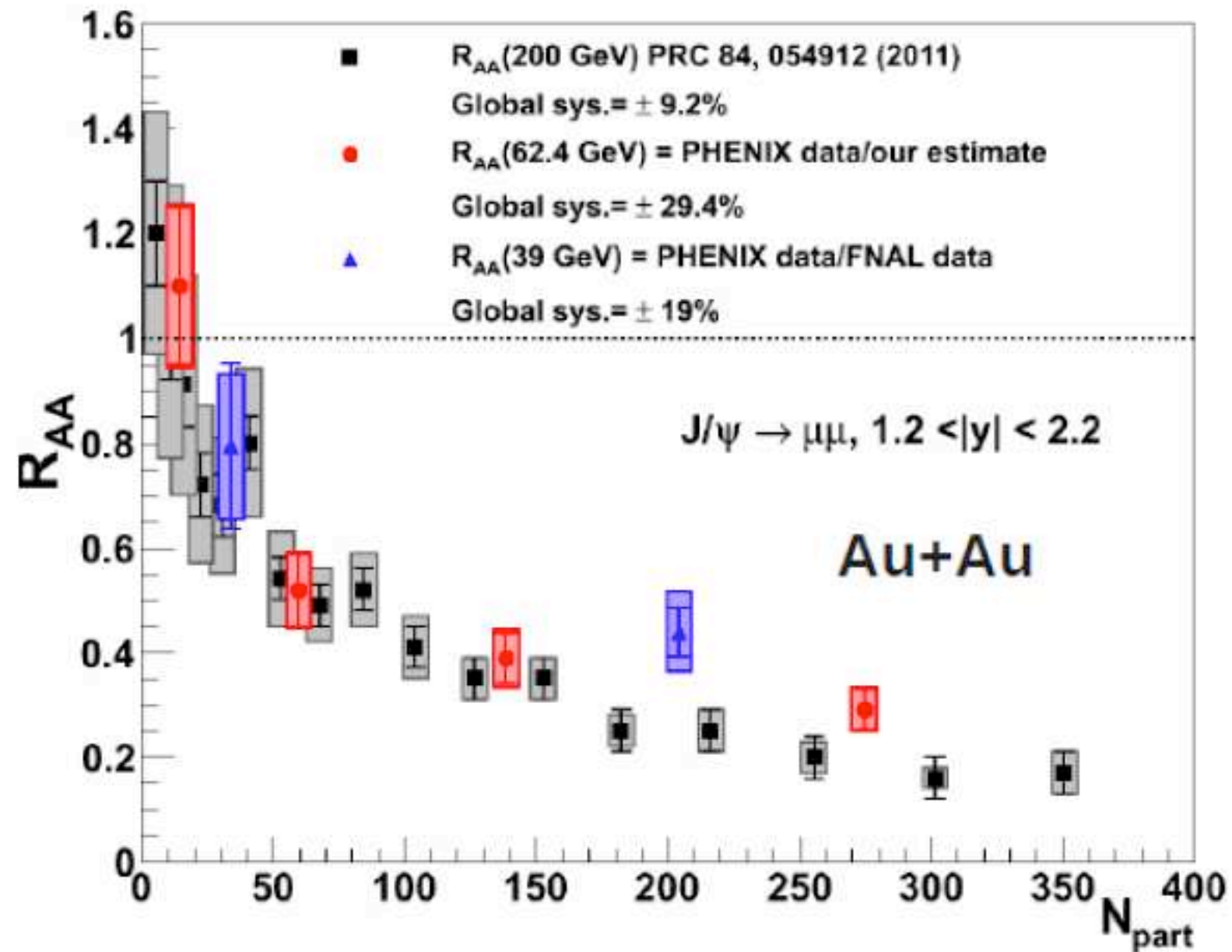


- Strickland, arXiv:1207.5327
 – Difficulties to simultaneously describe $\Upsilon(1S)$ and $\Upsilon(2S)$ with the same η/S value



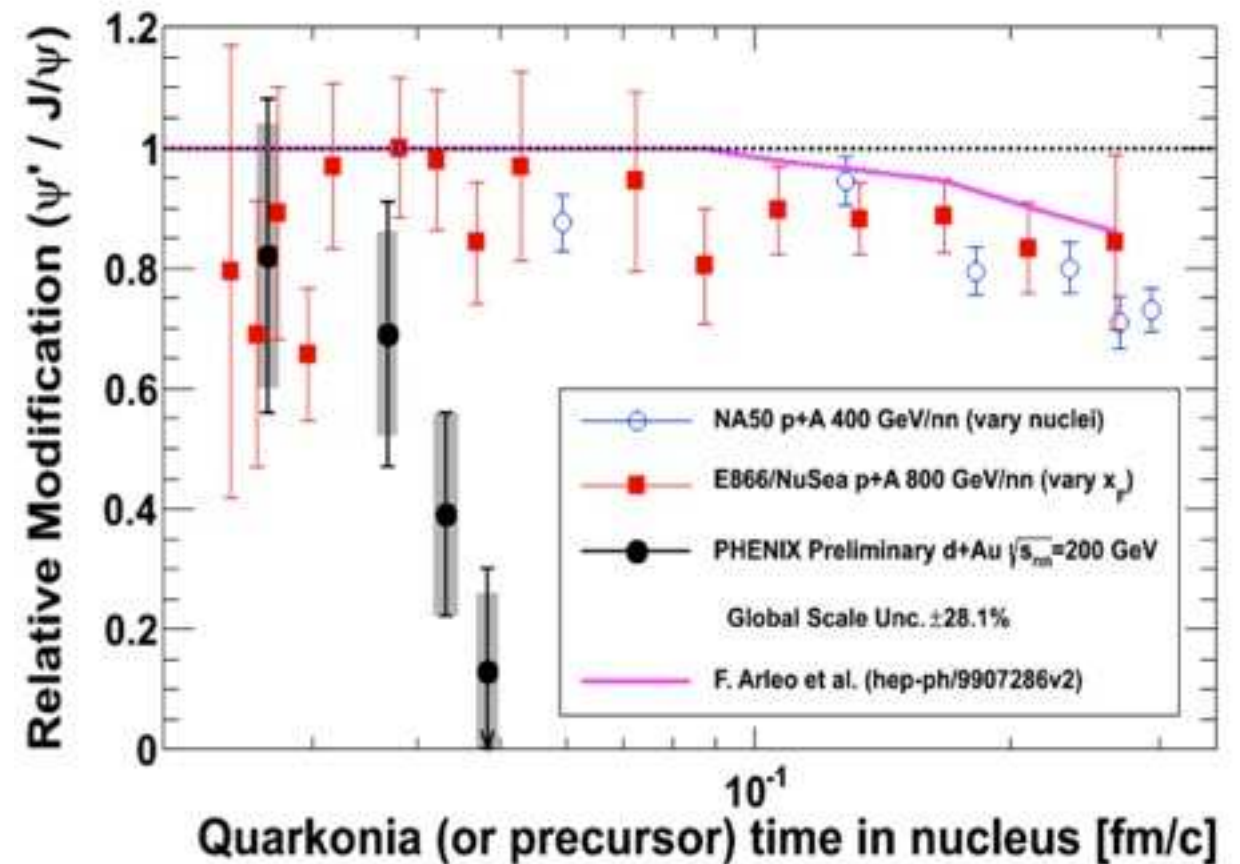
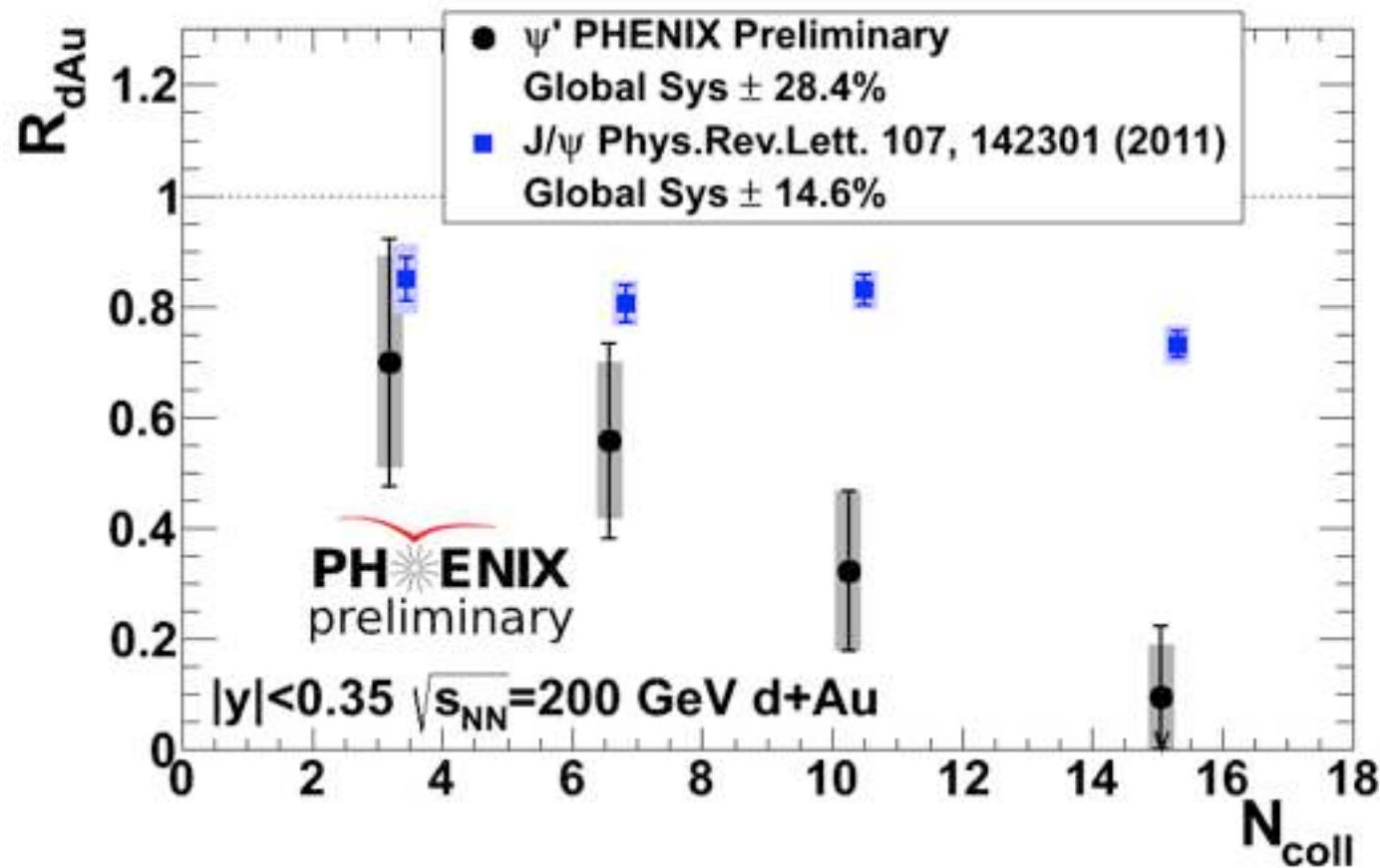
- Rapp et al., EPJ A48 (2012) 72
 Regeneration and nuclear absorption could be significant also for bottomonia!

Energy scan at RHIC

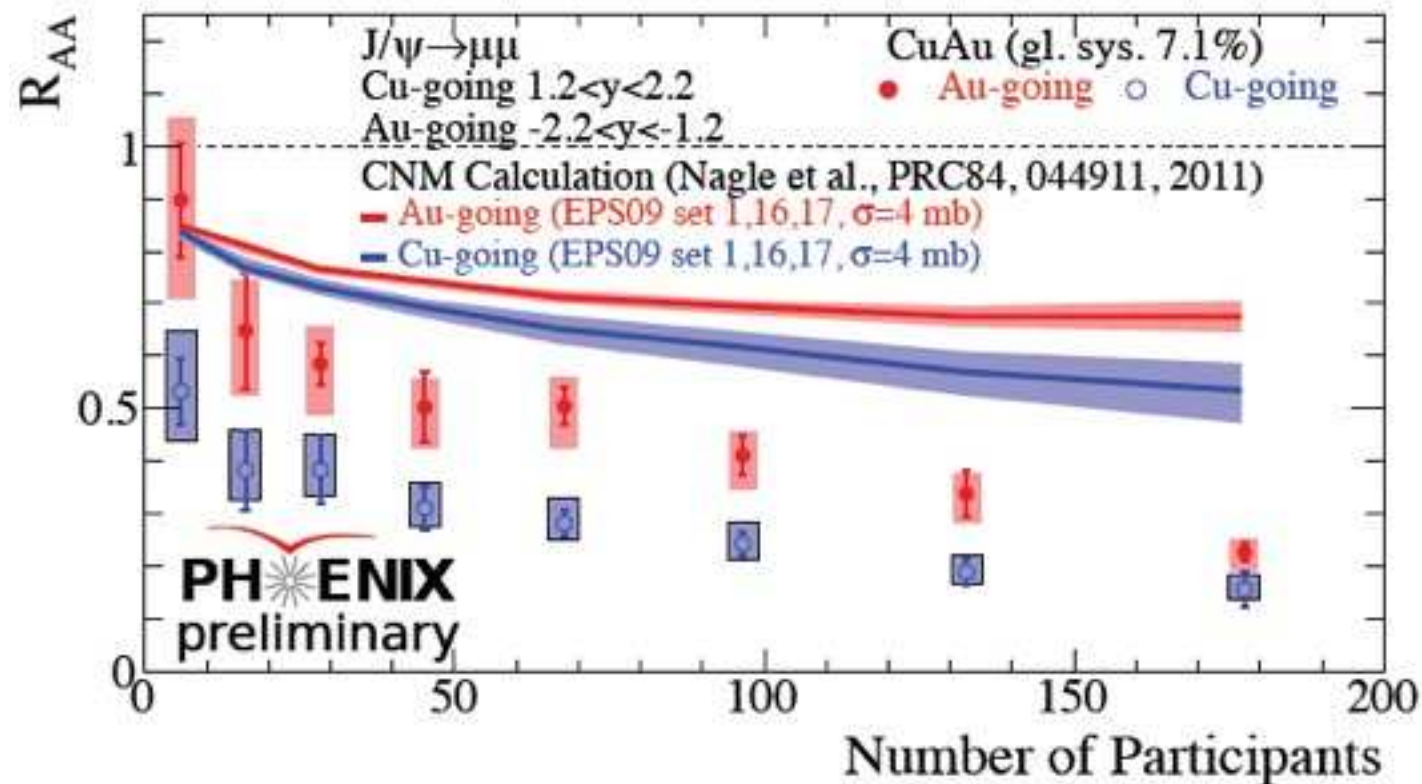
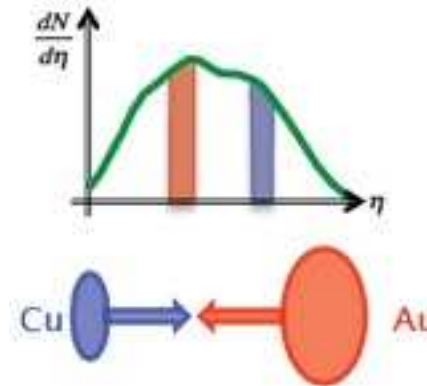


No dAu reference at 62.4 and 39 GeV

$\Psi(2S)$ also puzzling in d-Au



Different systems at RHIC



In Cu+Au collisions:

- $R_{AA}(\text{Au-going}) > R_{AA}(\text{Cu-going})$,
- qualitatively described by CNM but not quantitatively
- Additional suppression suggests hot, dense medium effect